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The Effect of Target Log Length on Log Recovery and Harvesting Cost: The Example of Short-Rotation Poplar Plantations

Raffaele Spinelli [1,2,3,*], Barnabáš Kováč [4], Patrik Heger [4], Dávid Heilig [5,6], Bálint Heil [5,6], Gábor Kovács [5,6] and Natascia Magagnotti [1,2,3]

[1] Consiglio Nazionale delle Ricerche-Istituto per la Bioeconomia (CNR IBE), via Madonna del Piano 10, Sesto Fiorentino, I-50019 Florence, Italy; natascia.magagnotti@ibe.cnr.it
[2] Australian Forest Operations Research Alliance, University of the Sunshine Coast (AFORA USC), Locked Bag 4, Maroochydore DC, QLD 4558, Australia
[3] Forestry Research Institute of Sweden (SKOGFORSK), Dag Hammarskjölds Väg 36A, S-751 83 Uppsala, Sweden
[4] IKEA Industry Slovakia, Továrenská 2914/19, SK-901 01 Malacky, Slovakia; barnabas.kovac@inter.ikea.com (B.K.); patrik.heger@inter.ikea.com (P.H.)
[5] Institute of Environmental and Nature Protection, University of Sopron, Bajcsy-Zs. u. 4., H-9400 Sopron, Hungary; dahe@hotmail.hu (D.H.); heilbalint2@gmail.com (B.H.); 62kovacsgabor62@gmail.com (G.K.)
[6] Ökoforestino Ltd., Ibolya út 11., H-9400 Sopron, Hungary
* Correspondence: raffaele.spinelli@ibe.cnr.it

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Abstract: Log production is the main target of new short-rotation poplar plantations, and their profitability depends on maximizing log yield. The authors set up a controlled experiment to determine the log yield increase obtained by shortening log length specification from 4 to 2 m, and to quantify the additional cost incurred by this change. The experiment indicated that reducing log length specifications allows a significant increase (+40%) in log yield in low-yielding (<25 BDT ha^{-1}) plantations, only. Such increase is matched by a parallel increase in harvesting cost (+33%) that must be balanced against the recovered additional value. Measures are suggested to mitigate the harvesting cost increment, such as: dual log length specifications, modifications of the forwarder load bay and changing from cut-to-length to whole-tree harvesting.

Keywords: CTL; forwarder; logging; productivity; biomass

1. Introduction

Over the last thirty years, poplar farming systems have differentiated into at least three main groups, which one may label according to their main target products as follows: lumber, chips and pulpwood. The "lumber" system was designed in the early 1900s with the main purpose of supplying furniture factories with locally produced lightweight veneer that was easy to process, treat and paint. These early industrial plantations developed from traditional farming systems common all across Europe and are still very popular in many countries [1]. Later on, and following the oil crisis of the 1970s, farmers started planting poplar to produce large amounts of low-cost energy wood, aimed at supplying the biomass-fed power plants that would supplement conventional fossil-based energy systems [2]. Those two farming systems aimed at opposite goals and followed completely different strategies: the "lumber" system was designed to maximize the value of the final harvest and used relatively long rotations (10–14 years), proper tending (pruning, spraying, etc.) and careful merchandising [3]. In contrast, the "chips" system was designed to minimize supply cost through coppice regeneration, very short rotations (2–3 years), reduced tending and simplified harvesting (i.e., whole-tree chipping) [4].

The third system—which we have labelled as "pulpwood" for convenience—represents an intermediate solution between the "lumber" and the "chips" systems and borrows elements from both of them, with the goal of combining a relatively small management cost with a richer crop than just bulk biomass [5]. First of all, the target product is neither high-value veneer logs nor low-priced whole-tree chips, but rather industrial roundwood that can be turned into pulp or boards, depending on the market. Therefore, rotations are longer than needed for chip production, but shorter than required for growing lumber, and normally range between 5 and 8 years. Harvesting must be careful enough to maximize the share of industrial roundwood, but not as meticulous as that for "lumber" plantations, given that the specifications for industrial logs are not as exacting as for lumber, and that the price differential between the logs and the chips obtained from logging residues is somewhat smaller. Nevertheless, the success of "pulpwood" plantations depends on a good balance between product value and management cost. Harvesting represents a most critical step, because it accounts for a significant proportion of the overall production cost, while representing that moment when value recovery can be maximized. For that reason, one wants to deploy harvesting techniques that are careful enough to prevent product degradation but still as productive as possible, in order to contain cost.

That issue is becoming increasingly urgent as many of the new plantations reach maturity. In the past few years, European wood industries have invested into the new crop with a view toward securing their raw material supply: today, many thousands of hectares are coming to maturity and need to be harvested within the next few years [6–8]. Given the relative novelty of those crops, no standardized set of harvesting methods has been developed and managers are still experimenting with system selection [9–12].

A first and basic question concerns log length. On one hand, reducing log length should lead to increased value recovery by dampening the effect of excessive stem sweep and taper [13]. A shorter log length allows rectifying curved long logs and capturing that stem portion that would not make it to the minimum small end diameter (SED) specification when extending further towards the top. On the other hand, shorter logs require more time to process [14] and to load [15], which will eventually lead to lower productivity and increased harvesting cost.

Therefore, the goals of this study were to compare the effect of two alternative log length specifications on value recovery and harvesting cost in short-rotation poplar plantations. In particular, the two log length specifications were 2 m and 4 m, and the questions addressed in this study were: what is the value recovery increase potentially obtained by shortening log length specifications, and what is the associated increase in harvesting cost? Obviously, the null hypotheses were those of no significant difference between treatments for value recovery and cost.

The two alternative log length specifications were tested in January 2022 on two among several plantations established in western Slovakia by IKEA Industry for supplying their factory in Malacky. There, poplar growing is integrated with the development project for an innovative high-value lightweight board that specifically relies on poplar wood for achieving its superior qualities. As a result, there is strong interest in maximizing the yield of pulpwood logs from those plantations, while keeping rotation within the 6th year mark due to management considerations. For that reason, IKEA Industry has been experimenting with varying log size specifications, both in terms of log length and small end diameter (SED) [16].

2. Materials and Methods

The experiment reported in this paper focused on the two main log length alternatives mentioned above (i.e., 2 and 4 m) as applied to plantations with different development characteristics: high-yielding and low-yielding. The high-yielding test plantation was located in Gajary (48°29′10.87′′ N; 16°55′25.52′′ in WGS84), while the low-yielding one was located in Pernek (48°23′55.04′′ N; 17°04′43.97′′ in WGS84), both sites being within a few kilometers from the IKEA factory in Malacky.

Both sites were characterized as “warm temperate, fully humid, with hot summer climate” (Cfb) according to the Köppen–Geiger classification. The mean annual temperature was 11 °C in the 2014–2020 interval, and the average annual precipitation was 742 mm. Soil texture was sand in Gajary and loamy sand in Pernek. Weather during all of the test period was consistently warm and reasonably dry, with occasional small precipitations. The air temperature during the trial period ranged between −2 and +14 °C.

Both plantations were 6-year-old poplar stands established at a square spacing of 3.0 m × 2.0 m with hybrid poplar (Populus × euramericana Dode (Guinier)). A mix of the three clones (AF13-16-18) was planted in Pernek, while pure "AF18" clone was planted in Gajary [17–19].

Harvesting was conducted according to the mechanized cut-to-length method, using the classic combination of a harvester and a forwarder. The same Rottne H8D harvester (125 kW, 10 t own weight, head EGS 406) and Logset 5F GT compact forwarder (140 kW, 15 t own weight, 12 t payload capacity) were deployed at both sites (Figure 1). Each machine had its own operator, who was a qualified forestry professional with significant experience with his machine and specific task. The operators were selected after observing more than a dozen contractors and excluding those operators that were not considered representative of the regional pool of professional drivers.

Figure 1. The harvester (**left**) and the forwarder (**right**) used for the experiment.

Before starting the experiment, both operators were informed about the purpose and the methods of the study and asked for consent to participate. They both released their consent and did their best to assist with the trial. They also worked at least one full day on the plantation outside the marked sample plots in order to familiarize themselves with the study routine and methods before the researchers engaged with experimental data collection. The harvester head measuring system was checked and calibrated on 10 trees before starting the experiment. Afterwards, calibration was checked on 2 trees at the beginning of each working day. Harvest instructions were the following:

Treatment A—manufacture all logs to a 2 m length and a 7 cm SED specification
Treatment B—manufacture all logs to a 4 m length and a 7 cm SED specification

The experimental design was a factorial scheme where each treatment was repeated 8 times on each site, that is: 2 treatments × 2 sites × 8 repetitions = 32 repetitions.

Each repetition consisted of one sample plot measuring approximately 15 m × 50 m (700 m^2). Plot width was selected to accommodate the work frontage of the harvester, which cut 5 row swathes (5 × 3 m = 15 m). Plot length was chosen to include about 130 trees, which would be the number normally cut in about one scheduled machine hour (SMH) according to previous studies of the same machine and plantation types. The experimental plots were alternately assigned to the two treatments, on the assumption that a pure randomized design could be confusing for the operators and increase the potential for attribution errors, while the alternate checker-board design would still allow an even spread of eventual gradients with less potential for confusion. The beginning and the end of each experimental plot was clearly marked with high-visibility paint to facilitate attribution. The circumference at breast height of all trees in all plots was measured manually with a measuring tape and then divided by Pi to obtain the diameter at breast height (DBH), over bark. Furthermore, 6 trees of every clone, covering the whole DBH distribution, were destructively sampled to determine their total height and the weight of the biomass potentially obtained from them, separately for the log and the chip components [20,21]. That allowed building a logarithmic DBH–height curve and an allometric equation for estimating the standing mass on each individual plot [22]. The homogeneity of even-aged clonal poplar made it possible to build reliable allometric functions with such a small sample [23–25]. In any case, mass estimates were later adjusted using ad-hoc correction factors obtained by matching the total log and biomass estimates against the actual amounts taken to the weighbridge available at the receiving factory. Correction factors consisted of the ratio between weighbridge figures and inventory figures (i.e., weighbridge tons/inventory tons). That was achieved separately for the log and for the chip portion obtained from each of the two treatments, at each of the two sites (8 correction factors). Moisture content (i.e., water mass fraction) was determined both at the time of destructive sampling during the inventory and at the time of delivery to the factory, so as to match dry mass pre-harvest estimates against dry mass post-harvest measurements. In both cases, moisture content was determined with the gravimetric method, according to EN ISO 18134-2:2015. Mean moisture content at delivery was 55% (standard deviation = 2.9%).

Depending on site and treatment, the ratio between factory dry mass and inventory dry mass varied from 0.53 to 0.99, with an overall average at 0.76—meaning that the field inventory overestimated actual harvest by about 24%.

At the time of harvesting, researchers determined for each sample plot the productive time consumption of the harvester and the forwarder, using a stopwatch accurate to the second [26]. Delay time was recorded but excluded from the study, where it was replaced by a 20% delay factor. That was done because the time spent on each sample plot was not long enough to accurately estimate delay time. The 20% increase applied to the data was consistent with the findings of previously published studies, with special reference to the harvesting of plantation forestry [27]. That figure was also quite close to the sum of all delays recorded during the complete study, as conducted on the 32 experimental plots.

Since the mass of wood on one experimental plot would often be smaller than the capacity of the forwarder, material from more than one plot was consolidated into the same load. While loading time could be accurately attributed to the respective sample plots, the attribution of travel and unloading time was performed on the basis of the number of grapple loads associated with each sample plot. If one plot required 30 grapple loads for loading and the second plot in that same load required an additional 30 grapple loads, then travel and unloading time were split evenly between the two plots. Obviously, care was taken to consolidate loads from the same treatments, so that the main factor determining the number of grapple loads required to pack one experimental plot was actual wood mass—not the handling quality of the assortment being loaded. On each site, all wood harvested from the experimental plots was taken to the same landing, and, therefore, the extraction distance was the same for both treatments on test. In any case, distance was estimated from Google Earth pictures, from the center of the sample plot to the center of the landing: that figure averaged 350 m in Gajary and 365 m in Pernek.

The plot-level time study was accompanied by a parallel cycle-level elemental time study [28]. That would cover about half of the harvester cycles on each sample plot, and all of the forwarder cycles. The goal of this study component was to determine if the change in log length would specifically impact cycle time, and if the 2 m log length treatment resulted in an increase in the number of logs per tree that was more than double compared with the number obtained under the 4 m log length treatment, all other factors being equal. That would prove that the shorter log length treatment did lead to an increase in log volume recovery. The cycle level time study also allowed identifying those cycles that would not produce even one log and determining if the proportion of those cycles was smaller in the shorter log length treatment, which could also be taken as an indicator of better log volume recovery. In turn, the elemental time study of the forwarder would easily show if the shorter log length would be slower to load and/or unload.

Machine costs were assumed to be the rates actually charged by the service providers. These were: EUR 69 per scheduled machine hour (SMH) for the harvester and EUR 53 SMH^{-1} for the forwarder. The authors acknowledge that individual rates can hardly offer a general benchmark and encourage readers operating under very different economic environments to recalculate harvesting costs using their own rates and the productivity data presented in this paper. Ideally, one should use official rates when available, but that was not the case in this study. However, the rates charged by the service providers selected for the study were in line with those charged by other service providers in the region—so that even if not official, the selected rates might be considered generally representative of the area. On the other hand, those rates are much lower than charged by neighboring Austrian contractors, located just across the border—which stresses the need for recalculating cost whenever market conditions differ significantly from those described in this paper.

The plot-level study data were used to quantify log yield, machine productivity and treatment cost (dependent variables) as average values, and the differences between alternative treatments (independent variables) were checked using the general linear model (GLM) technique, which is considered both accurate and robust against violations of the main statistical assumptions [29]. In any case, compliance with the normality and the homoscedasticity assumptions was checked with the Ryan–Joiner test and the Levene's test, respectively. Furthermore, a visual inspection of the residual plots was conducted after running the GLM procedure. Multiple comparisons were conducted with the Tukey–Kramer test.

In the case of log yield, those analyses showed that violations were strong, and, therefore, non-parametric statistics were deployed (Mann–Whitney unpaired comparison test conducted on each of the four treatment level combinations).

For all analyses, the significance level was set at $\alpha < 0.05$. The analyses were implemented with the software Minitab 17 (Minitab LLC, State College, PA, USA), one of the most popular statistical software applications in the field of engineering [30].

3. Results

The plantation in Gajary was much better developed than that in Pernek, due to higher site fertility and/or better clonal selection (Table 1). In particular, trees had a 25% higher diameter and were 80% taller: field stocking was over twice as large. On the other hand, no significant differences were found between blocks on the same site and assigned to the different treatments, and, therefore, one may state that the log length comparisons were conducted under the same field conditions on each of the two sites.

Table 1. Stand characteristics.

Site		Gajary	Gajary	Pernek	Pernek
Log length	m	2	4	2	4
Obs	n°	8	8	8	8
Clones	Type	AF18		Mix (AF13-16-18)	
Plot	BDT	3.44^{a}	3.75^{a}	1.49^{b}	1.65^{b}
DBH	cm	12.3^{a}	12.1^{a}	9.6^{b}	9.8^{b}
Height	m	14.6^{a}	14.6^{a}	8.0^{b}	8.1^{b}
Stocking	BDT ha^{-1}	44.0^{a}	48.1^{a}	19.3^{b}	21.4^{b}

Notes: BDT = bone-dry tons (0% water mass fraction); DBH = diameter at breast height; different superscript letters on mean values on the same row indicate a statistically significant difference at the 5% level.

In general, productivity was lower and cost higher for the shorter log length specification. Productivity also decreased and cost increased when moving from the high-yielding to the low-yielding plantation (Table 2). Impacts were especially strong on the felling and processing task and in the log forwarding task. Felling and processing productivity was between 50% and 60% higher in the high-yielding field compared with the low-yielding one and decreased by 20% to 5% when changing from a 4 m to a 2 m log length specification. Log forwarding productivity was unchanged between sites for the 4 m log length specification but dropped sharply (−50%) and significantly when the 2 m log length specification was introduced to the low-yielding site. In contrast, the biomass forwarding task was affected by neither field stocking nor log length.

Table 2. Harvesting productivity and cost.

Site		**Gajary**	**Gajary**	**Pernek**	**Pernek**
Log length	M	2	4	2	4
Obs	n°	8	8	8	8
Felling and	BDT SMH^{-1}	2.5 ^{a}	3.1 ^{b}	1.5 ^{c}	2.0 ^{a}
Processing	€ BDT^{-1}	28.4 ^{ab}	23.3 ^{a}	45.1 ^{c}	34.3 ^{b}
Forwarding	BDT SMH^{-1}	3.7 ^{ab}	5.2 ^{a}	2.6 ^{b}	5.6 ^{a}
Logs	€ BDT^{-1}	14.6 ^{ab}	12.1 ^{a}	23.4 ^{b}	11.9 ^{a}
Forwarding	BDT SMH^{-1}	4.7 ^{a}	5.0 ^{a}	4.1 ^{a}	4.8 ^{a}
Biomass	€ BDT^{-1}	11.8 ^{a}	11.0 ^{a}	13.3 ^{a}	11.5 ^{a}
Total cost	€ BDT^{-1}	41.8 ^{a}	33.8 ^{b}	61.2 ^{c}	46.1 ^{a}
Log yield	%	64.5 ^{a}	62.1 ^{a}	36.8 ^{b}	25.5 ^{c}

Notes: BDT = bone-dry tons (0% water mass fraction); SMH = scheduled machine hour, including delays (20%); different superscript letters on mean values on the same row indicate a statistically significant difference at the 5% level.

Essentially, harvesting the low-yielding site (Pernek) with mechanized CTL technology incurred a 35–45% higher cost than harvesting the high-yielding site (Gajary) with the same technology. Shifting to the shorter log length specification (2 m) determined an increase in harvesting cost that was estimated at between $\frac{1}{4}$ (Gajary) and 1/3 (Pernek) above the baseline cost for the 4 m log length specification treatment. In return, the shorter log length specification allowed a 44% increase in log yield, but only at the low-yielding site, while no significant log yield increase was achieved at the high-yielding site.

The analysis of variance (ANOVA) indicated that site effect was dominant and twice as large as log length effect when it came to total harvesting cost and harvester performance. Conversely, site selection had a weak effect on log forwarding and became significant only in combination with log length effect, which was the main driver. Biomass forwarding was unaffected by either factor (Table 3).

Regression analysis was used to describe the combined effect of field stocking and log length specification on overall harvesting cost, from standing trees to log and biomass piled at the roadside landing. The relationship was a non-linear one, so data was first linearized and then regressed. Least square regression allowed estimating a highly significant equation that compensated the point cloud (Figure 2) quite well and explained a large proportion of the overall variability in the data set (Table 4).

The effects of site and log length specifications could be better understood by a detailed examination of the harvester and forwarder work routines.

Table 3. Results of the ANOVA associated with the GLM.

	Model Fit	Effect	DF	SS	Eta^2	F-Value	*p*-Value
Total cost	S = 5.27	Site	1	2012	0.51	72.3	<0.0001
€ BDT^{-1}	Adj. R^2 = 0.78	Log length	1	1068	0.27	38.4	<0.0001
		Interaction	1	104	0.03	3.75	0.0629
		Residual	28	779	0.20		
Harvester	S = 0.32	Site	1	7.47	0.58	69.3	<0.0001
Productivity	Adj. R^2 = 0.74	Log length	1	2.45	0.19	22.8	<0.0001
BDT SMH^{-1}		Interaction	1	0.02	0.00	0.2	0.6793
		Residual	28	3.02	0.23		
Harvester	S = 4.27	Site	1	1528	0.58	835	<0.0001
Cost	Adj. R^2 = 0.78	Log length	1	513	0.20	28	<0.0001
EUR BDT^{-1}		Interaction	1	66	0.03	3.6	0.0680
		Residual	28	512	0.20		
Forwarding	S = 1.85	Site	1	0.85	0.01	0.25	0.6230
Productivity	Adj. R^2 = 0.24	Log length	1	38.9	0.28	11.3	0.0022
BDT SMH^{-1}		Interaction	1	4.4	0.03	1.3	0.2623
Logs		Residual	28	96.2	0.69		
Forwarding	S = 7.73	Site	1	147	0.06	2.48	0.1270
Cost	Adj. R^2 = 0.22	Log length	1	389	0.16	6.51	0.0160
EUR BDT^{-1}		Interaction	1	166	0.07	2.78	0.1060
Logs		Residual	28	1672	0.70		
Forwarding	S = 0.86	Site	1	1.48	0.06	2	0.1683
Productivity	Adj. R^2 = 0.08	Log length	1	2.38	0.10	3.22	0.0834
BDT SMH^{-1}		Interaction	1	0.23	0.01	0.3	0.5791
Biomass		Residual	28	20.7	0.84		
Forwarding	S = 2.24	Site	1	7.78	0.05	1.55	0.2230
Cost	Adj. R^2 = 0.05	Log length	1	12.9	0.08	2.58	0.1190
EUR BDT^{-1}		Interaction	1	2.08	0.01	0.42	0.5240
Biomass		Residual	28	140.31	0.86		

Notes: BDT = bone-dry tons (0% water mass fraction); SMH = scheduled machine hour, including delays (20%).

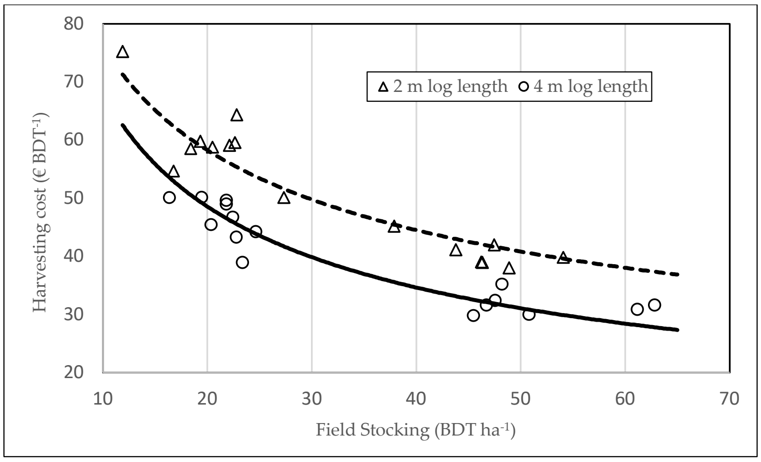

Figure 2. Relationship between total harvesting cost and field stocking.

Site had a much stronger effect on harvester performance than did log length specification: measured in terms of the total sum of squares, the effect of site was 2 to 5 times as strong as that of log length specification. However, the latter was still visible and could partly offset site selection—that is: under the 2 m log length specification, productivity in the high-yielding site dropped to levels that were not statistically significant from those achieved in the low-yielding site under the 4 m log length specification (although the difference was still visible). Conversely, under the 2 m log length specification, the number of biomass-only trees in the low-yielding site dropped to levels that were not significantly different from those achieved in the high-yielding site under the 4 m log length specification (but again, a difference was still visible) (Table 5).

Table 4. Regression equation for associating harvesting cost with field stocking and log length specifications.

Cost (EUR BDT^{-1})= a + b × $Stocking^{-0.452}$ + c × 2 m Log R^2 adj. = 0.908; n = 32; F-Value = 153.7; RMS = 3.432				
	Coeff	**SE**	**T**	***p*-Value**
a	−2.957	3.039	−0.973	0.3386
b	199.487	13.550	14.722	<0.0001
c	9.717	1.220	7.965	<0.0001

Note: BDT = bone-dry tons; stocking = BDT ha^{-1}; 2 m log = indicator (dummy) variable for the 2 m log length. Specification: if log length specification is 2 m, then = 1, otherwise = 0; SE = standard error.

Table 5. Results from the cycle-level study conducted on the harvester.

Site		Gajary	Gajary	Pernek	Pernek
Log length	m	2	4	2	4
Observations	n°	8	8	8	8
Time consumption	s $tree^{-1}$	29^{a}	24^{b}	21^{bc}	19^{c}
Productivity	trees PMH^{-1}	126^{a}	152^{ab}	182^{bc}	195^{c}
Logs per tree	n°	3.3^{a}	1.4^{b}	0.9^{bc}	0.4^{c}
Uneven log count	%	48^{a}	NA	29^{b}	NA
Biomass trees	%	4^{a}	12^{ab}	39^{bc}	59^{c}

Note: PMH = productive machine hour, excluding days. Uneven log count = trees that under the 2 m log length specification yield an uneven number of logs, meaning that the last log (bonus log) would have not been obtained under the 4 m log length specification. Biomass trees = trees that did not yield any logs—either 4 m or 2 m; different superscript letters on mean values on the same row indicate a statistically significant difference at the 5% level.

As to forwarder work, loading and unloading were the tasks most affected by log length specifications and site: the former could impact log handling characteristics, the latter was related to overall log size and load concentration—both of which were obviously larger at the high-yielding site. An analysis of loading and unloading time consumption (s BDT^{-1}) showed that both log length and site had a significant effect on the time spent loading and unloading logs, which was 20% to 100% longer for the 2 m log length specification, especially on the low-yielding site (Figure 3). Both effects were significant, but log length effect was at least three times stronger than site effect.

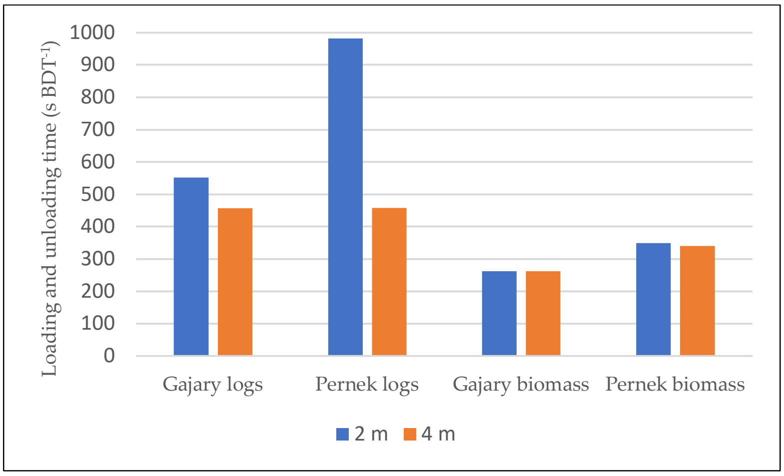

Figure 3. Loading and unloading efficiency for the two sites, log length specifications and feedstock types.

Conversely, the time spent loading and unloading biomass (i.e., lop and top) was affected by site only, and was 30% longer on the low-yielding site, compared with the high-yielding one. That effect was statistically significant.

4. Discussion

First of all, one must address the main limitation of this study: testing just one operator per machine type. Since the operator was the same for both treatments on test at both sites, the comparison remains valid, but one may question whether the results of this (valid) comparison had not been unduly affected by the subjective abilities of the individual operators [31]. Basically, one cannot exclude that the largely increased time consumption recorded under the shorter log length treatments may have been caused by poor operator skill, and that more dexterous operators may have been less hindered by the decreased log length. That remains a possibility, especially for the forwarder, given that reducing log length would indeed make log loading and unloading more difficult, and those tasks are largely manually controlled (i.e., not automated). Conversely, the main change caused by a decreased log length on harvester work is one that can be largely automated by pushing a button, so one may expect operator dexterity to be less critical. In any case, both operators were experienced and qualified professionals, selected from a larger pool of service providers as representative samples, and their individual performance should reflect those expected by most operators available for short-rotation poplar (SRP) harvesting in the region [32].

For that reason, one may generalize the results of this study, although with some caution. In fact, the figures presented here find strong corroboration in the results of earlier published studies. In particular, this study estimated the harvester productivity loss caused by a decrease in log length specifications at between 20 and 25%, and that figure is matched quite well by the 22% loss found by Belisario et al. [33] or by the 30% loss found by Spinelli et al. [14]—both referred to eucalypt short-rotation plantations that offered work conditions similar to those found in the SRP covered in this study. Outside of plantation forestry, a decrease in log length specifications has also been shown to cause a significant decrease in harvester productivity, although not as large (10%) [34]. Similar corroboration can be found for the effect on log forwarding efficiency: several earlier studies do report an inverse relationship between log length specifications and forwarding productivity—especially when it comes to the loading and unloading tasks [35–38]. As a matter of fact, a seminal Nordic study suggests 3.6 m as the threshold log length below which loading productivity is severely reduced [39]. Other studies indicate that halving log length specifications may lead to halving loading productivity [15,33,34], which is what was found here for the low-yielding site.

It is noteworthy that the strongest effects were obtained on low-yielding plantations. That applies to both desirable and undesirable effects: respectively, the increased log yield and the decreased harvesting efficiency. It seems logical that the log yield impact is especially strong on weak plantations, where tree size is often too small for offering a 4 m log. Incidentally, that may explain why the 2 m log length specification is most popular in European short-rotation eucalypt plantations, while longer log length specifications are favored in the southern hemisphere [40], where growth conditions are much more favorable and eucalypt trees are far bigger than their European homologues at the time of harvesting [41]. Therefore, decreasing the log length specification is worth considering only when plantation yield is poor. In that case, the first thing to do would be to weigh the financial losses incurred through lower harvesting productivity against the gains obtained from better value recovery; then, the second would be to try minimize losses and boost gains, regardless of where the scales have tipped, since one can always try recovering a loss or increasing a profit.

Unfortunately, the price tag placed on the two assortment types—logs and biomass—is still proprietary, so the first exercise cannot be shown here. In fact, even if viable, that exercise would not be generally meaningful, since price tags rapidly change with place and time; for managers, it is enough to know what the productivity losses and log yield increases are: then, they can apply those figures to their own price tags and check whether a reduction in log length specification will pay or not.

On the other hand, one can think of a few measures for mitigating the productivity losses derived from a decrease in log length specifications. That is especially easy with forwarding, since short logs are routinely forwarded in small-tree operations and dedicated adaptations have been developed for facilitating that task [42]. In particular, one may consider crosswise loading, possibly after fitting the forwarder bunk with side panels to contain the load, as done in the Iberian eucalypt plantations [43]. Even more radical (and potentially more effective) would be a change in harvesting system, whereby trees are extracted whole and merchandised at the landing [44]. That would also facilitate an alternative strategy, whereby 2 m long logs are produced only when the available stem or stem portion cannot offer a 4 m log. CTL machines are normally designed for producing multiple sorts from the same stem and therefore it would be extremely easy to set two different log length specifications on the control panel and shift between them according to need. If applied at the stump site, such solution could make forwarding a bit more complicated [45], but it would have no impact on extraction efficiency when applied at the roadside landing, after extraction. In fact, if trees are processed at the roadside landing, then one might resort to multi-tree processing technology, otherwise it would too cumbersome for in-field access. That would be the case with chain-flail delimbers, which can be adapted to handle relatively weak trees [46] and could offer a viable solution to efficient small-tree harvesting.

5. Conclusions

When applied to low-yielding (<25 BDT ha^{-1}) short-rotation poplar plantations, changing the log length specifications from 4 m to 2 m boosts log yield by 40%, but it also incurs a harvesting cost increase of 33% over the baseline figures recorded under the 4 m log length specification. In contrast, no significant log yield increases are obtained in high-yielding (>35 BDT ha^{-1}) plantations, despite the 25% increment in harvesting cost. Therefore, the shorter log length specification should be applied to low-yielding plantations only, possibly in conjunction with some additional measures aimed at mitigating the harvesting cost increase, such as modification of the forwarder loading space, adoption of dual length specifications, and/or a shift from the CTL to the WTH system.

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