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Abstract

The success of short-rotation coppice (SRC) will rise with increasing biomass prices. One of the main constraints for establishing SRC today is the unpredictable cost of (whip) harvesting. Therefore, the harvest of a 9 ha SRC in Belgium was monitored, in order to develop a whip harvesting cost model to estimate harvesting productivity and costs as a function of various input data. The harvest was executed in February 2017 with a Stemster MkIII, after a three-year rotation of SRC with poplar. A biomass inventory was combined with a time-motion study and an economic analysis. The field stocking (fresh weight basis) ranged from 40-100 Mg ha^{-1}. The average load of 2.4 Mg was obtained from a 220 m long double row and took 6.4 min, resulting in an average productivity of 26 Mg h^{-1} (excluding delays). Genotype, field stocking and their interaction significantly affected the harvester's productivity. Border limited headlands (< 8 m width) had a significant impact on turning time and, thus, increased the total harvesting cost by 6%. The offload time was stable at 23 s Mg^{-1}, while the harvesting cost varied from 7 to 22 € Mg^{-1}, depending on work conditions and costing assumptions. Even though the Stemster MkIII produces whips instead of wood chips, its productivity is still lower than the modified foragers' productivity, but the Stemster MkIII is lighter and may offer better mobility. Optimal performance can be obtained with a high field stocking, appropriate spacing and adequate headlands.

Highlights

- The Stemster reached an average harvesting productivity of 26 Mg h^{-1}, excluding delays.
- The harvesting cost varied between 7 and 22 € Mg^{-1}.
- Constrained headlands significantly decreased the Stemster's efficiency.
- Field stocking was negatively correlated to harvesting cost (per Mg).
- Differences among poplar genotypes significantly affected harvest efficiency.

Keywords

Belgium; biomass; harvesting cost; modelling; *Populus* spp.

1. Introduction

European agriculture has a large potential for biomass production, which is indispensable for supporting the new bio-economy. Agriculture can provide sugar- and oil-based feedstocks, and can also supply large amounts of ligno-cellulosic raw material derived from three main sources: fibre residues from conventional food crops, specialized herbaceous fibre crops, and dedicated tree plantations. Among these options, tree plantations have been the least successful so far, mostly due to technical hurdles that have limited their profitability compared with the alternatives [1]. However, this situation may change as a result of the rapidly increasing demand and prices driven by an expanding bio-economy. Within this framework short-rotation wood crops established on set-aside agricultural land may capitalize on their capacity to produce large amounts of fibre [2] in combination with important environmental benefits, in contrast to conventional agriculture [3, 4].

Among the various cellulosic cropping systems, short-rotation coppice (SRC) seems well aligned with the expectations of farmers, who are used to short investment return times and not in favour of traditional wood plantations, harvested at 10-30 years intervals [5]. The SRC concept has been intensively tested for over 30 years, even at a commercial scale and in several countries. Despite current unfavourable market conditions SRC is a commercial reality that accounts for many thousands of hectares in Italy and Sweden.

Profit margins on bio-energy from SRC are limited and the success of supply chains based on SRC requires efficient management. In particular, care should be devoted to optimizing rotational harvesting operations, which account for almost half of the total SRC production costs [6] and for one third of the total SRC energy inputs [7, 8]. Since the early 1980's several dedicated SRC harvesters have been developed and tested [9] and a number of machines have reached serial production and relative commercial success [10]. At present, the sector is dominated by heavy cut-and-chip harvesters, based on powerful industrial harvesters and available in different makes and models [11].

These machines owe their success to their high cost effectiveness, high productivity and simplified operation management, because cutting, collection and comminution are performed in one single pass [12]. With few exceptions, these are the machines preferred by machine contractors, who already own one or more foragers and may profit from extending their use to SRC during idle seasons [13].

The main problem with single pass cut-and-chip harvesters is the production of wet chips, with a high moisture content depending on the tree species, the season of harvest and other local parameters and could vary between 50% and 60% on a fresh weight basis [14]. This high moisture content requires that the chips be utilised before substantial decay occurs [15]. Attempts to control storage conditions can hardly curb microbial activity, which eventually determines quality degradation and dry matter losses [16]. The relatively small volumes of SRC chips harvested today facilitate just-in-time delivery and immediate utilization, which favours the dominance of cut-and-chip technology. However, the predicted expansion of SRC may impose that increasing amounts of product are stored over extended periods, given the seasonal character of SRC production [17]. Chips can either be treated or covered to restrict degradation, or chipping should be postponed until final use and the product should be stored as whole stems (whips). Compared with chips, stems are not only less vulnerable to microbial decay , but they lose moisture during storage [18], which generally leads to a higher product quality and more efficient transportation [19].

While much financial and research resources have been devoted to the development of efficient cut-and-chip machinery, this development is still ongoing for the cut-and-collect equipment. A few reliable machines have been developed over time, some of which are now commercially available and could be actually deployed [20]. A recent review highlights a large imbalance, i.e. the cut-and-chip harvester tests outnumber the cut-and-collect harvester tests by 8 to 1 [21]. Prospective users can choose among a number of productivity models for at least four different cut-and-chip harvester makes, applied on poplar [10], willow [22], black locust [13] or eucalyptus [23]. Yet, no model is

available for predicting the performance of any cut-and-collect harvester, despite the availability and commercial use of these machines.

Therefore, the goal of this study was to develop a productivity model for a cut-and-collect harvester, capable of estimating productivity output and cost as a function of various field variables as: row length, headland space, field stocking and genotype selection. Such a model may assist farmers, contractors and supply managers when planning production, negotiating rates or scheduling transport. Furthermore, the model was developed using the same structure of similar models already available for the cut-and-chip harvester, as to allow simple comparisons between these two types of machines.

2. Materials and methods

2.1 Experimental SRC field

This research was carried out on the POPFULL (http://uahost.uantwerpen.be/popfull/) SRC plantation, located in Lochristi, Belgium [51°06'44" N, 3°51'02" E; 24]. The site was established in April 2010 [25] and it had already been harvested twice before the current trial: on 2-3 February 2012 [12], and on 18-21 February 2014 [26]. Therefore, the trial of this study represented the third coppice harvest, which was conducted on 28 February and 1 March 2017, after a three-year rotation. The total area of the plantation harvested in 2017 amounted to 9 ha, and contained 12 commercially available poplar (*Populus* spp.) genotypes. All genotypes were planted as mono-genotypic blocks (henceforth referred to as blocks) of at least six double rows each, with an overall planting density of 8 000 ha^{-1} (Figure 1). Hardwood cuttings were planted in a common double-row scheme; the narrow and the wide rows were respectively 75 cm and 150 cm wide, and the distance between cuttings within a row was 110 cm. Chemical, mechanical and manual weeding was performed during the first growing season after planting; herbicides were applied a second time after the first harvest in 2012

and a third time after the second harvest in 2014. Neither irrigation nor fertilization has been applied since establishment.

Yield was estimated in terms of above-ground woody biomass (AGWB) for each block, using the same procedure as with previous harvests [27]. The number of shoots per stool was counted for every stool in one row per block, and the shoot diameters of all shoots per stool were measured for every fifth stool in the same row. Shoot diameters (D) were measured with an accuracy of 0.01 mm at 22 cm height with a digital calliper (Mitutoyo, CD-15DC, UK). Inventories were made in winter, during the dormant stage. From these data the stool mortality at the time of harvesting was determined. Furthermore, a genotype-specific allometric relation was established between D and AGWB (fresh matter). This was done by manually harvesting ten random shoots per genotype, covering the widest diameter range. Shoots were cut at 7 cm height (i.e. to approximate the expected harvesting height) and weighed with a precision scale. Their diameter at 22 cm height was also determined with a digital calliper, and a power function was fitted to the data in order to obtain the AGWB per shoot as a function of diameter at 22 cm (D), as from the equation :

$$AGWB = a \times D^b \qquad \text{(Eq. 1)}$$

where a and b are regression parameters.

The AGWB per stool was obtained by summing the AGWB of all shoots on each of the sampled stools. The inventory data were considered spatially representative per block and therefore the average AGWB per stool was calculated. This value was multiplied with the actual (surviving) density per block, in order to obtain the field stocking. AGWB values represent fresh biomass under field conditions, including a water mass fraction estimated at ca. 50%.

2.2 Harvesting machine and performance study

The cut-and-collect harvester used for the study was the Nordic Biomass Stemster MkIII, which is the most established harvester of this type in Europe (Figure 2). The machine consists of a bogie trailer (four wheels) that carries a pair of disc saws, a double belt conveyor and a deck with bottom chains for unloading. As the machine advances, the twin saws cut the stems while the conveyor grabs them and moves them to the deck. Once full, the deck can be unloaded by activating the bottom chains. The harvester is designed to be drawn by a farm tractor (>100 kW under solid terrain conditions or frozen terrain, or >135 kW under soft terrain conditions), which also delivers power through its power take-off (PTO). Since all harvester functions are hydraulic, the PTO is directly connected through a cardan shaft to the hydraulic pump on the harvester. During the study, the harvester was hitched to a 175 kW John Deere 8220 farm tractor. The harvester-tractor unit was specifically equipped for use on soft terrain, and the harvester bogies were fitted with floatation tracks while the tractor wheels had been replaced with rubber tracks (rice paddy option). The machine was driven by an experienced operator, who had specific knowledge of the technique and the fields since he had also performed the previous harvest in 2014 using the same machine.

Before harvesting begun, all obstacles were removed; the edge stools that were too close to the ditches or too big (diameter > 15 cm or height > 8 m) for the harvester were cut with a chainsaw or mechanically with a small feller-buncher. Operating costs were calculated using the procedures described by Miyata [28]. Costing assumptions are reported in Table 1. In particular, repair and maintenance cost was estimated at 50 % of depreciation, and labour cost was set at 25 € h^{-1}. Fuel cost was assumed to be 0.90 € L^{-1} (subsidized fuel for agricultural use). The total costs are inclusive of 20 % profit and overheads.

Machine performance was determined with the time-study technique, applied at the cycle level in the snap-back mode [29]. A deck load was defined as the individual repetition and the time to collect a full deck was determined with a Husky Hunter hand-held computer, running the dedicated time-study software Siwork 3 [30]. Productive time was split into three time elements: (i) harvesting, as

the machine cuts the stems and feeds them to the deck; (ii) turning at the field's edge; and (iii) offloading the deck in the field, once this was full. All delay time was recorded separately and associated with notes describing the cause for the delay, so that it could be later reclassified into four main delay categories: mechanical; operational; personnel; and study [31]. Eventually, study delays were excluded from the database, because they were not considered representative of actual work conditions. All momentary blockages of the saws or the conveyor were considered functional to the harvesting process and were included with harvesting time.

For each cycle the researcher also recorded the row ID (associated with the individual mono-genotypic blocks) and the weight reported on the electronic on-board scale installed on the Stemster deck. It was, thus, possible to associate each time record with a specific block, surface area, genotype and AGWB weight. In particular, the on-board scale weights were corrected against the results of the pre-harvest inventory conducted for the same genotype and block, although the error was small (1.1%). Furthermore, the distance covered during turns was recorded with the GPS unit, because this distance was variable and depended on how many rows the harvester would skip between exiting the field and re-entering it. The researcher also indicated if the turn occurred at a border limited (< 8 m) or at a regular (≥ 8 m) headland. The database of the time study was then joined with a second database containing information about the row lengths of the original plantation, from which the shortened rows were updated with field measurements.

2.3 Analyses

The study allowed building a solid database that contained information of 110 full cycles (deck loads). Descriptive statistics were used for reporting the main results of the study, separately for each time element. In the end the goal of the study was to build the following model:

Total worksite time = Harvest time (incl. blockage) + Turn time + Offload time + Delay time (Eq. 2)

Therefore, the analyses aimed to determine factor effects on each time element. To do this, data was first checked for linearity and normality by observing residual plots and distribution histograms, respectively. Equality of variance was checked with Levene's test. Stocking and cycle time data complied with all statistical assumptions, whereas harvest time per unit product (s Mg^{-1}) data were non-normally distributed, but they could be normalized through logarithm transformation. Normal (or normalized) data were tested through the analysis of covariance (ANCOVA), with the aim of determining the significance and the strength of all relevant effects, especially stocking and genotype. Eventual differences were allocated to the specific treatments using Tukey-Kramer's test. Time element data were also analysed with multiple regression techniques to estimate significant relationships between time consumption and relevant variables. The effect of categorical data was introduced by generating suitable indicator variables [32]. All statistical analyses were conducted with the SAS Statview 5.01 software package, for $\alpha < 0.05$.

Significant regression equations were used to assemble a simple deterministic model, capable of returning SRC collection costs as a function of user-entered independent variables. This model did not require complicated programming and could be effectively assembled in Excel. The simplicity of the model reflected a comparatively simple process that involved a single unit and did not need to account for interface (interaction) delays. Furthermore, more realistic, complex simulation models were not considered to increase much prediction accuracy when used on such simple process chains [33]. Deterministic spreadsheet models have already been used for estimating the cost of agricultural harvesting operations, such as sugar cane harvesting [34] or pruning residue collection [35]. The following model conditions were applied: 200 m row length (study mean); 5 ha field size; turning with re-entering at every 5th row; and adequate headland space (≥ 8 m). The costing assumptions were kept the same as in Table 1. The incidence of delay time was set at 20% of total worksite time and preparation was estimated at 50 min per day, both figures being consistent with the result of other longer term studies of SRC harvesters [10, 36]. A sensitivity analysis was conducted for the

effects of genotype Grimminge and of area limited headlands (< 8 m). The model has been published as supplementary materials to the manuscript and can be accessed through the journal website.

3. Results

The average field stocking was 70.8 Mg ha^{-1} and ranged from 40 Mg ha^{-1} for genotype Grimminge to 100 Mg ha^{-1} for genotype Bakan (Table 2). Average row length was 202 m with an average yield per row of 2.8 Mg. Statistical analysis allowed grouping the genotypes in three classes, depending on field stocking (Figure 3). Bakan, Robusta and Skado belonged to the high field stocking class, yielding ca. 90-100 Mg ha^{-1} at the end of the three-years rotation; Grimminge belonged to the low field stocking class, yielding ca. 40 Mg ha^{-1} at harvest. All other genotypes belonged to the intermediate class, with yields most commonly between 60-70 Mg ha^{-1} at the end of the rotation. Different genotypes also showed different yield variability, with vesten showing the widest yield variation (26-117 Mg ha^{-1}). Genotypes Koster and Muur also offered variable yields, ranging from ca. 40 Mg ha^{-1} for the worst plots to ca. 100 Mg ha^{-1} for the best ones. While not overly productive, Ellert proved the least variable genotype, with yields consistently close to 65 Mg ha^{-1}.

Concerning harvesting performance, the mean row load amounted to 2.4 Mg and was obtained from an on average 202 m long row, with a stocking of 70.8 Mg ha^{-1}. Mean cycle time (one average double row) was 6.5 min, excluding delays. Therefore, net productivity averaged 26.0 Mg per productive machine hour, excluding all delays (Table 3).

Harvesting time per Mg was significantly affected by field stocking, genotype and their interaction (Table 4). The effect of field stocking was exponential, but the variable was linearized in order to use a multiple linear regression (Figure 4). Genotype Grimminge had a significant effect (Tukey-Kramer test) on harvesting time per Mg; therefore an indicator variable for this genotype was generated and introduced into the multiple linear regression as the interaction variable Grimminge x stocking

(linearized). The resulting regression was highly significant and had a coefficient of determination of 0.823 (Table 5).

Mean turning time was 156 s if the headland was adequate (≥ 8 m) and 195 s if it was area limited (< 8 m), and this difference was statistically significant. In fact, turning time was directly proportional to the distance between the exit row and the re-enter row, which varied with work pattern and operator preference. Both turning distance and headland standards were entered as independent variables into a multiple regression and returned a reasonably good estimate (Table 5). Offload time was constant among different blocks and genotype, and averaged 64 s for a mean load of 2.4 Mg, or 22.8 s Mg^{-1} (Table 3). The incidence of delays was very small and accounted for 9% of total worksite time. This was considered too small for representing long-term performance, and therefore the deterministic model was built with a dedicated delay dialogue case, where users can enter the value they consider most representative of their working conditions.

Depending on field stocking, headland characteristics and genotype, harvesting cost varied between less than 7 € Mg^{-1} to over 22 € Mg^{-1}. Other model factors being equal, lack of adequate headlands resulted in a 6% cost increase. Since it was easier to harvest, genotype Grimminge allowed for an 8% harvesting cost reduction, within the field stocking range that characterizes this genotype.

4. Discussion and conclusions

Genotypic comparison was not among the goals of the study, but collateral information was eventually gathered about genotypic performance, which could be of some practical interest. However, the yield data reported in this study are only valid for one specific site and one rotation. Yield variability depends on resiliency of genotypes to soil and climatic conditions, pests and diseases. Low variability might indicate good resilience to environmental factors and a stable resprouting vigour in the third rotation. The yield data represent fresh biomass, including the water mass fraction. Water content may vary with genotype, and therefore the differences reported here

may change once they are referred to dry biomass [37]. Lastly, cut stems are not forwarded or comminuted with the cut-and-collect harvesting system, in contrast to the cut-and-chip harvesting system. Removal from the field, comminution and road transport inflict some losses, thereby reducing the actual yield.

The model was based on one field trial only and some assumptions were made. The operator of the Stemster was very experienced and also conducted previous harvests at the studied SRC. Another variable not included in the model is the shape of the field, which was not regular (cfr. Figure 1) and might have had an influence on harvester performance. Furthermore, the models developed with this study are rather simple, and there are other more sophisticated approaches that could have offered better resolution. However, simpler models were preferred because they are easier to understand by the larger community of practitioners, and they are most easily replicated by fellow scientists regardless of their skills with statistics

Machine cost is relatively high, but the SRC harvester is only produced in small quantities and manufacturing is not industrialized. A large expansion of the SRC planted surface area would generate a larger demand for dedicated equipment, leading to industrial production and a possible reduction of investment cost. For example, a 20% reduction in investment cost for the Stemster would reduce the harvesting cost with 0.5 € Mg^{-1}. In any case, our costing assumptions are contingent to the specific work conditions encountered in this study, and may need to be adjusted for different work conditions. The spreadsheet model is, therefore, made available to readers, who can recalculate costs after introducing those assumptions that best reflect their own work conditions.

The model is logical and its operation is relatively easy to explain. The direct relationship between field stocking and SRC harvester productivity is well known and can be generalized across the whole range of machine types and models [21]. The merit of this study is to offer specific parameters for such relationship when using the Stemster MkIII. Furthermore, the study detected and quantified the

effects of genotype selection and of headland characteristics for the first time. It demonstrated that genotype characteristics can affect harvesting productivity in more ways than just by offering a smaller or larger field stocking, as operators often state. Specifically, genotype Grimminge proved easier to harvest than other genotypes in this study, for the same field stocking, which appears to be related to stem form and the presence of fewer and larger stems on the same stool (Table 6).

Apparently, these characteristics of genotype Grimminge facilitated the cut and collection by this machine time and resulted in fewer temporary blockages that were included with harvesting time. Other harvesting machines may not be sensitive to the characteristics of Grimminge, but they might be sensitive to the specific characteristics of other genotypes. The influence of specific genotype traits has been demonstrated here for the first time, which will encourage other researchers to include genotype as a factor in future SRC harvester studies.

This study also quantified for the first time the impact of headland standards on harvesting cost. Inadequate headland space limits efficient operation [38], but no studies have been made on this aspect thus far. The results presented in this study only apply to the Stemster MkIII, because they depend on machine manoeuvrability and operation layout. A nimbler machine is likely less affected by headland constraints, while an operation requiring two machines to travel side by side (like for most cut-and-chip operations) might be more sensitive to headland standards. Yet, this study offers a first estimate that could be generalized, until specific studies will address other mainstream machine types.

Concerning operation layout this study only covered cutting and collection, not forwarding and comminution. In fact, the same Stemster MkIII could also be used for forwarding to the field edge, which was not the case in this study, where the loads were dumped in the field as soon as the deck was full. However, dumping in the field was considered most efficient: forwarding was performed later on with a dedicated forwarder priced at 85 € h^{-1}, not 197 € h^{-1}.

The productivity estimates confirm those of a previous study of the same machine, which reported a mean productivity around 20 Mg per productive machine hour (excluding delays) for a stocking in the range of 40 Mg of fresh matter ha^{-1} [36]. The regression model provides a moving benchmark that can return productivity and cost estimates as a function of working conditions. The model shows that productivity and cost may vary by a factor of three between the best and the worst case, emphasizing the importance of managing operation and field conditions to achieve financial sustainability.

In conclusion, with a harvesting productivity of ca. 26 Mg h^{-1} the Stemster MkIII performed very well under difficult conditions: the terrain was inaccessible for heavy modified forage harvesters and the harvested stems of the SRC plantation were too large to be handled by mower-chippers. The cost for harvesting was very variable and depended on the available headland space, on the field stocking, and on the growth habit of the different poplar genotypes.

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6. References

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Table 1 - Machine costing for the cut-and-collect harvester unit

Element		Tractor	Harvester
Make		John Deere	Stemster
Model		8220	MkIII
Purchase price	€	230000	230000
Economic life	years	5	10
Resale value	% new	30	30
Interest rate	%	4	4
Fuel consumption	L h^{-1}	18	0
Crew	n°	1	0
Depreciation rate	€ $year^{-1}$	32200	16100
Annual use	h	1000	600
Total fixed cost	€ h^{-1}	45.4	42.6
Fuel & lube	€ h^{-1}	22.2	0.0
Repair & maintenance	€ h^{-1}	16.1	13.4
Personnel cost	€ h^{-1}	25.0	0.0
Total variable cost	€ h^{-1}	63.3	13.4
Overheads (20%)	€ h^{-1}	21.7	11.2
Total	€ h^{-1}	130.5	67.2

Notes: h = scheduled machine hour, including delays

Table 2 - Field stocking (Mg ha^{-1}) at the end of a three-year rotation for the different genotypes

Genotype	Mean	SD	Minimum	Maximum
Bakan	103.4^{a}	12.6	79.8	117.4
Robusta	95.2^{a}	17.5	73.6	121.9
Skado	86.2^{a}	19.7	56.0	112.7
Wolterson	71.9^{b}	5.2	62.3	78.1
Vesten	70.6^{b}	26.3	26.1	117.6
Muur	69.1^{b}	17.0	45.4	100.8
Oudenberg	65.2^{bc}	6.0	58.0	76.1
Ellert	65.1^{b}	4.7	60.6	71.0
Koster	63.8^{bc}	16.5	38.4	104.6
Brandaris	57.4^{b}	9.9	44.4	75.4
Grimminge	41.2^{c}	7.4	27.8	48.2

Notes: stocking is expressed in fresh matter, including water mass fraction; SD = standard deviation; different superscript letters on the same column denote a statistically significant difference between means ($\alpha<0.05$).

429 Table 3 - General results of the harvester performance study

		Mean	SD	Minimum	Maximum
Row length	m	202	62	53	288
Turn distance	m	80	54	3	368
Load	Mg	2.4	0.9	0.5	5.4
Harvest time	s	220	68	57	413
Turn time	s	104	37	5	218
Offload time	s	64	27	18	214
Productivity	Mg h^{-1}	26.0	9.1	8.8	65.8
Stocking	Mg ha^{-1}	70.8	22.2	26.1	121.9

430 Notes: SD = standard deviation; Productivity is in Mg dry matter per productive machine hour, excluding delays.

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Table 4 - Results for the analysis of covariance (ANCOVA) of harvest time data

Effect	DF	SS	η^2	F-Value	P-Value
Genotype	10	0.059	0.12	1.88	0.0580
Field stocking	1	0.104	0.20	33.44	<0.0001
Interaction	10	0.072	0.14	2.33	0.0174
Residual	89	0.277	0.54		

Notes: DF = Degrees of freedom; SS = Sum of squares; η^2 = size effect, i.e. the ratio of the SS for the specific factor and the total SS.

Table 5 - Regression equations for harvesting time and turning time. For explanation of variables and parameters, see text.

Harvest time = a + b $FS^{-0.823}$ + c $FS^{-0.823}$ Grimminge				
R^2 adj = 0.823; n = 110; F = 255.083; p <0.0001				
	Coeff	SE	T	P-value
a	-14.33	4.422	-3.24	0.0016
b	2829	138.9	20.37	<0.0001
c	-334.3	91.74	-3.64	0.0004
Turn time = a + b d + c Constrained				
R^2 adj = 0.385; n = 146; F = 46.313; p <0.0001				
	Coeff	SE	T	P-value
a	109.4	7.148	15.30	<0.0001
b	0.639	0.078	8.176	<0.0001
c	35.64	7.773	4.585	<0.0001

Harvest time = s Mg^{-1}, including blockages; n = number of valid observations; SE = Standard error; FS = Field stocking (Mg ha^{-1}); Grimminge = indicator variable for genotype Grimminge: if genotype is Grimminge = 1, if another genotype = 0; Turn time = s $turn^{-1}$; d = distance between exit row and re-enter row (m); Limited = indicator variable for area limitedheadland: if headland is < 8m = 1, if headland ≥ 8 m = 0.

Table 6 – Characteristics related to the growth habitat of the different poplar genotypes harvested, at the time of harvesting.

Genotype	average number of shoots stump^{-1}	average shoot diameter (mm)	mortality (%)
Bakan	6.1	30.3	17.3
Brandaris	12.6	20.5	15.8
Ellert	8.6	25.0	11.4
Grimminge	4.8	26.1	27.2
Hees	13.4	27.2	21.9
Koster	8.3	22.3	15.7
Muur	8.7	21.3	10.7
Oudenberg	7.7	20.2	14.1
Robusta	3.7	28.8	36.1
Skado	8.2	29.3	19.7
Vesten	7.0	28.2	26.7
Wolterson	12.6	18.7	18.6

Figure 1 - Plan of the experimental short-rotation coppice plantation with mono-genotypic blocks and row numbers

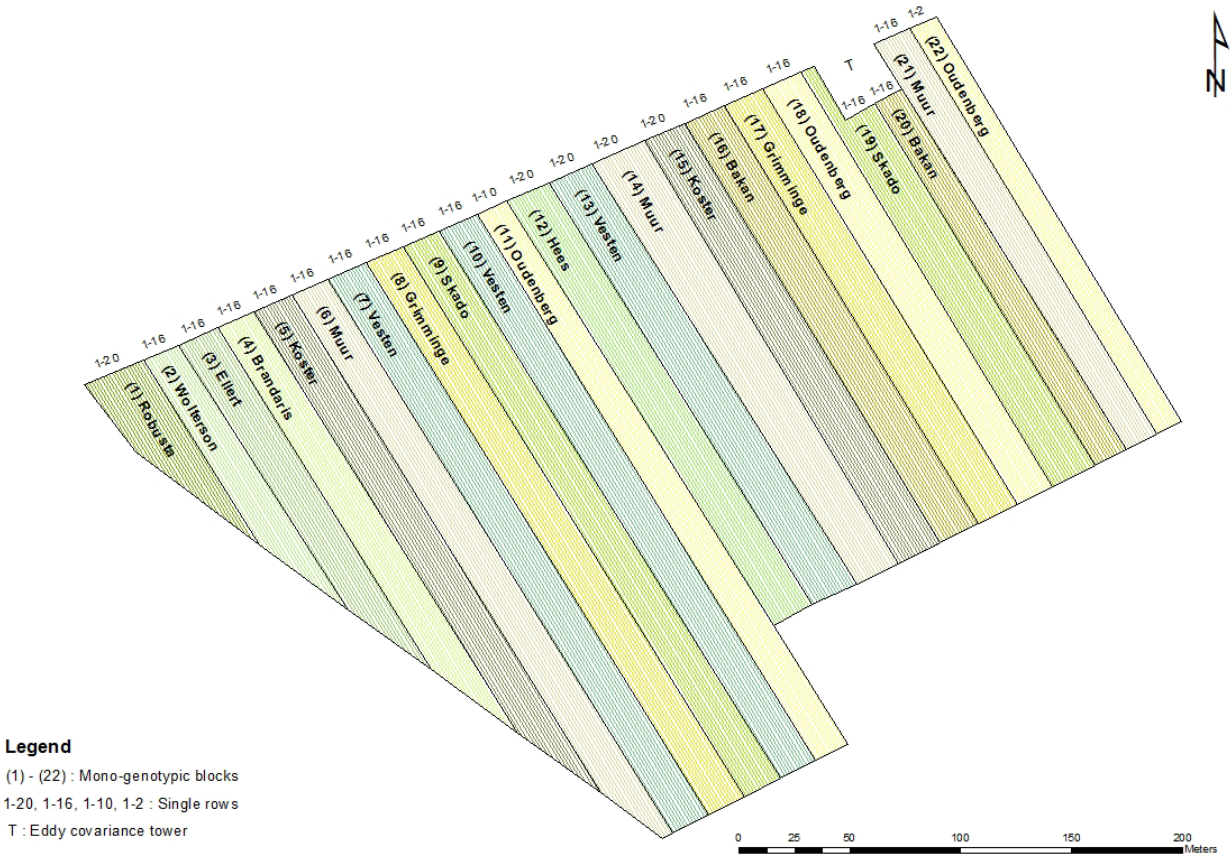
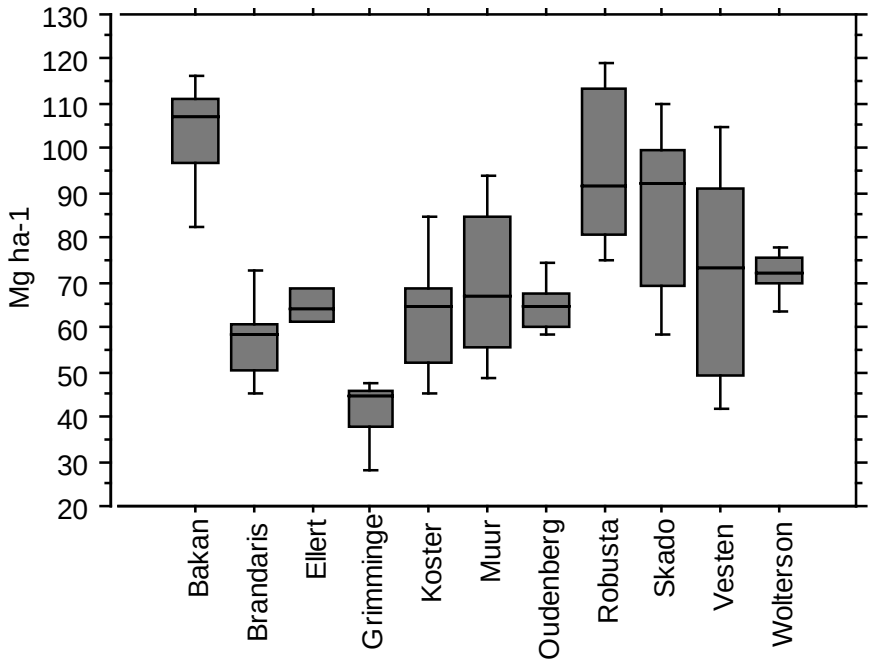


Figure 2 - The Stemster MkIII at work on the POPFULL SRC plantation

Figure 3 - Boxplot for field stocking (Mg ha^{-1}) for all 12 poplar genotypes



455 Figure 4 – Linearized relationship between harvest time per Mg and field stocking (full line). Triangles
456 represent genotype Grimminge and circles are all other genotypes. Equation details can be found in
457 table 5.

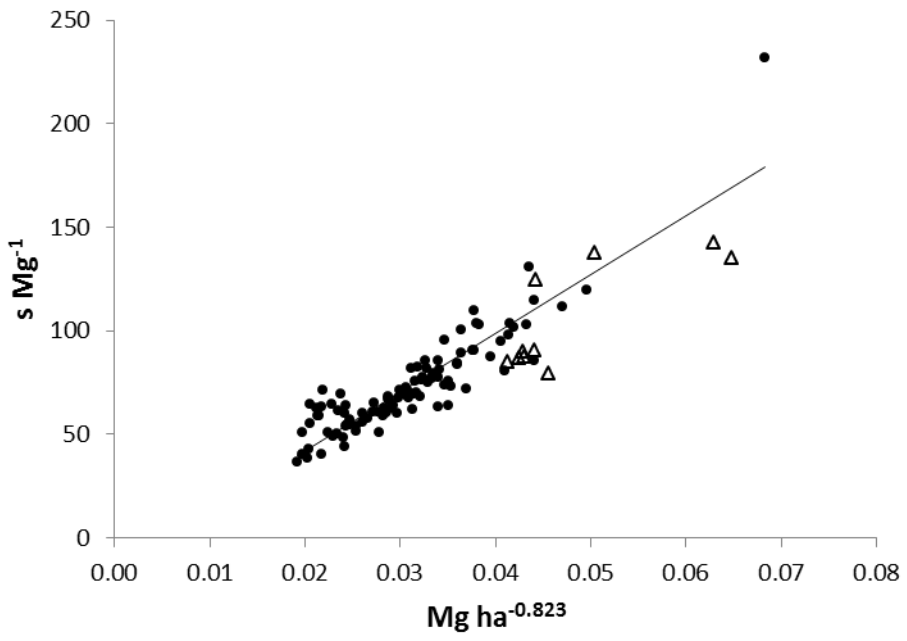


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Figure 5 - Harvesting cost as a function of field stocking for all genotypes (full black line), specifically for genotype Grimminge (full grey line) and for all genotypes when the headland would be area limited (dotted line). Weights are in Mg fresh matter.