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Comparative analysis of harvesting machines on an operational high-density short rotation woody crop (SRWC) culture: One-process versus two-process harvest operation

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ABSTRACT

Short rotation woody crops (SRWCs) are being studied and cultivated because of their potential for bioenergy production. The harvest operation represents the highest input cost for these short rotation woody crops. We evaluated three different harvesting machines representing two harvesting systems at one operational large-scale SRWC plantation. On average, 8 ton ha^{-1} of biomass was harvested. The cut-and-chip harvesters were faster than the whole stem harvester; and the self-propelled harvester was faster than the tractor-pulled. Harvesting costs differed among the harvesting machines used and ranged from 388 € ha^{-1} to 541 € ha^{-1}. The realized stem cutting heights were 15.46 cm and 16.00 cm for the tractor-pulled stem harvester and the self-propelled cut-and-chip harvester respectively, although a cutting height of 10 cm was requested in advance. From the potential harvestable biomass, only 77.4% was harvested by the self-propelled cut-and-chip harvester, while 94.5% was harvested by the tractor-pulled stem harvester. An increase of the machinery use efficiency (i.e. harvest losses, cost) is necessary to reduce costs and increase the competitiveness of biomass with other energy sources.

1. Introduction

Within the framework of the production of bioenergy from fast-growing trees, various aspects have already been studied and documented over the past decennia: importance of species and genotypes to be used [1,2]; impact of coppicing in short rotation cultures [3,4]; length of (coppice) rotation cycle [5,6]; interaction between soil type and genotype [7]. Theoretical studies and practical field experiments have led to the introduction of bioenergy plantations in several regions of the world. To bring the concept of the culture of bioenergy from the experimental to the commercial scale, efforts have been

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Abbreviations: SRWC, short rotation woody crop; NRB, not recovered biomass; UB, uncut biomass.

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made toward a further mechanization of the culture: mechanical planting, weed management [8], nutrient and herbicide applications, irrigation [9,10] and harvesting [11,12]. For most of the management operations existing agricultural techniques have been modified and applied. In a short rotation biomass culture agricultural management approaches are being applied to woody crops. Since the main difference between agricultural crops and woody biomass crops is in the harvest of the crop, progress on the mechanization of the harvesting process has been slow thus far [4,13].

Although different harvesting machines have already been developed, mainly two different harvesting approaches have been developed for short rotation woody crops (SRWCs), i.e. the harvest-and-chip system [14] and the harvest-and-storage system [15] (Fig. 1). The harvest-and-chip system can be performed with a self-propelled cut-and-chip front harvester or with a tractor-pulled cut-and-chip side harvester. In most cases the self-propelled cut-and-chip front harvester is a converted corn harvester with a specific coppice header for SRWCs. In both cases chips are produced from wet stems, collected in an attached trailer or an additional tractor–trailer combination, and stored as wet chips. The storage of wet chips implicates a risk of dry matter losses, and further drying might be necessary. In the harvest-and-storage system, wet stems are cut, transported to a storage location to dry, and chipped afterwards to obtain dry chips. The storage of cut stems, also called ‘rods’, avoids the problems with wet chips. The expected productivity is 35.6 Mg of fresh biomass per scheduled machine hour for the self-propelled cut-and-chip front harvester, and 19 Mg for the harvest-and-storage system, but with similar operational costs [14,15]. The lower the moisture content of the obtained chips, higher calorific values for energy conversion. An overview of additional advantages and disadvantages of each system can be found in earlier studies [14,15].

Machinery costs represent the highest input costs for biomass production (Silveira [33] cited in Hannum [12]). Consequently, harvesting costs make up a large share of the total costs of biomass produced from SRWCs and might amount up to 45% of the total cultivation costs [24]. This is due to the fact that harvesting is mostly subcontracted by the farmer, as a harvesting machine is excessively expensive to be owned and used by a single farmer. Typical harvest rates (excluding transportation costs) charged by Belgian and Danish subcontractors range from 400 € ha^{-1} for a tractor-pulled stem harvester, over 600 € ha^{-1} for a tractor-pulled cut-and-chip harvester to 950 € ha^{-1} for a self-propelled cut-and-chip harvester [24].

The present study extends previous analysis by: (i) evaluating three different harvesting machines representing two harvesting systems at the same plantation; (ii) assessing the efficiency and performance of these harvesters on a field plantation at an operational scale; and (iii) discussing the economic potential, advantages and disadvantages of the different harvesters and harvesting systems.

We have been operating and intensively monitoring an operational bioenergy plantation with fast-growing poplar and willow trees in Flanders, Belgium (see http://webh01.ua.ac.be/popfull) since three years. The plantation was harvested after the first two-year rotation cycle. In this paper we compare and report on the performance of the three harvesting machines that were used to harvest this large-scale SRWC plantation.

2. Materials and methods

2.1. *Description of the site*

The field site is located in Lochristi, Belgium (51°06’N, 03°51’E) and consists of a high-density poplar and willow plantation

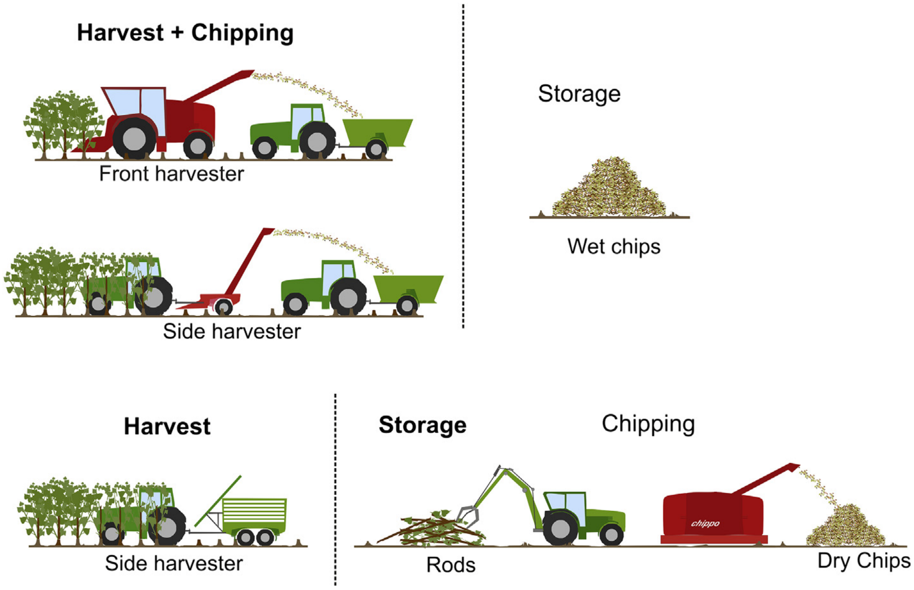

Fig. 1 – Representation of the harvest-and-chip and the harvest-and-storage systems. The harvest-and-chip system can be performed with a self-propelled cut-and-chip front harvesting machine or with a tractor-pulled cut-and chip side harvesting machine. In both cases the final product are wet chips. The harvest-and-storage system is operated using a tractor-pulled whole stem harvester. In this harvest system the final product could be dry chips at sizes and moisture demanded.

(POPFULL project; http://webh01.ua.ac.be/popfull). Lochristi is located 11 km from Ghent in the province of East-Flanders. After initial soil sampling and site preparation, 12 poplar (*Populus* sp.) and 3 willow (*Salix* sp.) genotypes were planted in monoclonal blocks in a double-row planting scheme on 7–10 April 2010 with a commercial leek planter [7]. The distance between the narrow rows was 75 cm and that of the wide rows was 150 cm. The distance between trees within a row was 110 cm, yielding an overall density of 8000 trees per ha. The total length of individual rows ranged from 45 m up to more than 325 m. An area of 14.5 ha was planted on a total of 18.4 ha of former agricultural (pasture and crop) land. Manual and chemical weed control was applied during the first and the second year. Neither fertilization nor irrigation was applied during the entire lifetime of the plantation thus far. A detailed description of the site, the plantation lay-out, the soil conditions and the planted materials have been published previously [7].

2.2. *Harvest operation and harvesting equipment*

On 2–3 February 2012 – i.e. after a first rotation cycle of two years – the entire plantation was harvested. For this harvest three different harvesting machines were used: (1) a self-propelled cut-and-chip harvester of New Holland (available in Belgium), (2) a tractor-pulled cut-and-chip harvester of Ny Vraa (transported from Denmark), and (3) a tractor-pulled whole stem harvester of Nordic Biomass (transported from Denmark) (Fig. 1). The first harvester is a front-operated single-pass cut-and-chip harvester of New Holland, consisting of a forage harvester (type: FR9090) and a coppice header (type: 130 FB). This harvester is mostly accompanied by an additional tractor–trailer combination to collect the biomass chips, as it was in our case. The second harvester is a side-operating and tractor-pulled single-pass cut-and-chip harvester, consisting of a tractor (type: JD 6920) equipped with a harvesting implement of Ny Vraa (type: JF Z200) and – if desired – with an attached trailer to collect (and automatically unload) the chips. In our case, this harvester was accompanied by an additional, separate tractor–trailer combination to collect the chips, instead of an attached trailer (Fig. 2). The third harvester is a side-operated tractor-pulled stem harvester of Nordic Biomass that consists of a tractor (type: JD 8520T) and a (inseparable) harvest–trailer combination (type: Stemster MKIII). This harvester does not need an accompanying tractor with trailer (Fig. 3). The three different harvesting systems are schematically represented in Fig. 1; their technical characteristics and financial information sheets are summarized in Table 1. The technical characteristics (weight, biomass storage, required power, etc.) as well as the sales prices of the tractor-pulled cut-and-chip harvester and the stem harvester were taken from the technical documentation available on the official website of the manufacturing companies, Ny Vraa and Nordic Biomass, respectively [16,17] completed with information acquired from personal communications with the managers of both companies (Table 1). The characteristics of the self-propelled cut-and-chip harvester were obtained from personal communication with Xavier Desmyter, who owns and operates the described harvester, and from a study by De Dobbelaere [18].

Fig. 2 – View of the tractor-pulled cut-and-chip harvester operating at the short rotation woody crop operating on willows.

The three harvesting machines harvested different parts of the plantation. The self-propelled cut-and-chip harvester harvested approx. 7 ha, while the tractor-pulled cut-and-chip harvester and stem harvester harvested 1 ha and 6.5 ha, respectively. Professionally skilled and experienced drivers operated the harvesting machines during the harvest. Before harvesting we had requested a cutting height of 7–10 cm above soil level to all 'operators'. A schematic representation of which parts of the plantation were harvested by each harvesting machine is shown in Fig. 4.

2.3. *Data collection during the harvesting operation*

The harvesting rate of each harvester was calculated by dividing the recorded total duration of the harvest of each harvesting machine by the actually harvested surface area by the machine. The tractor-pulled stem harvester harvested shorter rows and had to turn more than the self-propelled cut-and-chip harvester, giving the last mentioned harvesting

Fig. 3 – View of the tractor-pulled whole stem harvester (on the left) and the self-propelled cut-and-chip harvester with the trailer–tractor combination (on the right) operating at the same short rotation woody crop poplar plantation.

Table 1 – Technical and financial specifications of the three harvesting machines that were compared in this study. Specifications are based on the information provided by the manufacturers unless otherwise indicated. Source: for Stemster http://www.nordicbiomass.dk; for Ny Vraa http://www.nyvraa.dk; for New Holland De Dobbelaere 2011 and http://www.newholland.com.

Harvester/coppice head (type)	Stemster MKIII	130 FB	JF Z200-HYDRO/E
Tractor/basis machine (type)	JD 6920	FR9090	JD 8520T
Manufacturer harvester (company, country)	Nordic Biomass, Denmark	New Holland, Belgium	Ny Vraa, Denmark
Manufacturer tractor (company, country)	John Deere, USA	New Holland, Belgium	John Deere, USA
Principle of operation	Whole-stem harvester	Cut-and-chip	Cut-and-chip
Weight harvester (Mg)	7	13.1	1.5
Weight tractor (Mg)	6	N/a	6
Maximum harvestable diameter (cm)	15–20	10–15	4–6
Biomass storage capacity (Mg)	4.5	N/a	N/a
Cost of purchase (€)	175,000 (tractor) 215,000 (harvester)	350,000 (forage harvester) 85,000–90,000 (coppice head)	125,000 (tractor) 46,000 (harvester)
Horsepower (HP)	150	768	255

N/a: not applicable.

machine a competitive advantage in terms of harvesting rate. The stem harvester, however, was not able to harvest the long rows, as it was only able to collect rods from rows up to 200 m of length, before the storage capacity was reached. The plantation existed of several rows up to 300 m. The tractor-pulled stem harvester is only able to harvest such long rows if it is accompanied by a shuttle wagon which collects the harvested stems when the attached trailer is full before finishing the row. The tractor-pulled cut-and-chip harvester only harvested part of the willows at the plantation, as it was not able to harvest (poplar) trees with a diameter larger than 4–6 cm (see plantation lay-out, Fig. 4).

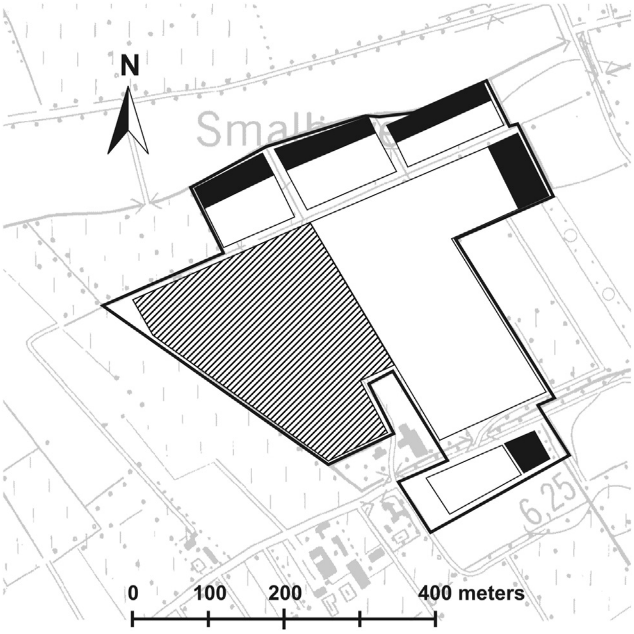

Fig. 4 – Lay-out of the short rotation woody crop plantation and harvested areas per harvesting machine. Black areas = willows area, harvested by the tractor-pulled cut-and-chip side harvester; hatched area = poplars area harvested by the tractor-pulled whole stem harvester; white area = poplars area harvested by the self-propelled cut-and-chip front harvester.

2.4. *Cost analysis*

To calculate the hourly costs of using the machinery for the harvest we used the guidelines of the American Agricultural Economics Association (AAEA) [19]. These costs were divided into operation and ownership costs [19]. The operation costs include maintenance, fuel, lubrication, and labor costs. The ownership costs include the depreciation costs, the opportunity costs associated with the financial capital invested in the assets and other costs such as property taxes, housing and insurance.

The fuel consumption by the different harvesters and by the tractor–trailer combination was recorded during the harvest (Table 2). We calculated the fuel costs, using a diesel price of 0.95 € l^{-1}, which was the official fuel price for agricultural use in September 2012 in Belgium [20]. For the remuneration of the machine operators we used the average Belgian hourly labor cost of 35 € h^{-1} [21]. Due to the transport of the harvesting machine to the field site and the time required to lubricate and service the machines, the actual hours of labor generally exceed the field machine time [19,22]. Therefore, we multiplied the hourly labor cost by 1.1 to calculate the labor costs required for the different harvest operations, as previously suggested by Edwards [22] and as applied by Smeets et al. [23] and El Kasmioui and Ceulemans [24].

The salvage values, required to compute the depreciation and opportunity costs, were calculated as a percentage of the purchase price based on the calculation methodology suggested by Bowers [25], and mentioned by the AAEA [19] (Table 2). We assumed a (economic) lifetime of 8 years for the harvesters, of 10 years for the trailer and of 12 years for the tractor. Given the limited land area of SRWCs in Belgium (and its neighboring countries) we assumed a moderate annual use of 500 h yr^{-1}, which corresponds to an annual harvestable area between 250 and 380 ha, depending on the operation rate. We assumed a higher annual utilization for the tractor and the trailer,

Table 2 – Overview of the costs and characteristics of the equipment (harvesting machine, tractor, trailer) used for the harvest of the short rotation woody crop plantation of this study.

Equipment	Purchase price (k€)	Annual use (h y^{-1})	Lifetime (y)	Maintenance costs (€ h^{-1})	Lubricant use (€ h^{-1})	Salvage value (k€)	Fuel use (l h^{-1})	Operation rate (h ha^{-1})	Operating and ownership costs excluding labor (€ h^{-1})	Harvest costs including labor (€ ha^{-1})	Combined tractor
Tractor – 150 HP	125	800	12	8.4	0.242	31.3	N/a	N/a	25.8		N/a
Tractor – 255 HP	175	800	12	11.8	0.397	43.8	N/a	N/a	36.2		N/a
Harvester – Ny Vraa	46	500	8	15.9	N/a	9.7	30	1.7	83.6	387.7	150 HP
Harvester – Nordic biomass	215	500	8	74.1	N/a	45.3	24	2	195.7	540.9	255 HP
Harvester – New Holland	437.5	500	8	52.5	1.233	92.2	33	1.3	212.5	464.1	N/a
Trailer – 40 m^3	44	800	10	15.6	N/a	7.8	20	N/a	41.7		150 HP

HP: horse power; N/a: not applicable.

however, as this equipment can be used for other agricultural purposes than the harvest of SRWCs.

The depreciation and opportunity costs were calculated using the capital recovery formula, which annualizes these two components together. This method amortizes the original costs of the asset (i.e. purchase price) less the present value of the salvage value over its lifetime to calculate the annual capital service cost (CSC) [19]:

$$\mathrm{CSC} = \frac{\mathrm{PP} - \frac{\mathrm{SV}}{(1+r)^n}}{\frac{1-\frac{1}{(1+r)^n}}{r}}$$

where PP is the purchase price of the machines (€), SV is the salvage value (€), r is the discount rate, and n is the lifetime of the equipment in years. The discount rate used in the calculations equaled 4% y^{-1}. Data on housing costs, property taxes and insurance vary widely from country to country and from farm to farm. We therefore calculated these costs as a percentage of the purchase price as suggested by the AAEA [19]. The AAEA suggested adding an annual cost of 2% of the purchase price to the CSC to calculate the annual ownership costs.

2.5. *Data collection after the harvest*

Harvest losses were estimated from samples collected at the field site after the harvest, i.e. early March 2012. These losses were only estimated in the area of the field site planted with poplar for reasons of comparison. In order to control the variability caused by different species and genotypes, losses were only measured in two poplar genotypes: i.e. Koster and Skado. Those genotypes were chosen because they are genetically and phenotipically contrasting and represented the range of productivity for the entire plantation (see Broeckx et al. [7] for more details of the genotypes). Woody stem biomass that was supposed to have been harvested, but remained on the field was considered as harvest losses. Two types of harvest losses were considered: (i) uncut biomass (UB) due to a different realized cutting height than the requested cutting height of 7–10 cm; and (ii) cut, but not recovered biomass (NRB) [26].

To estimate the UB, 20 stumps were selected randomly on the areas harvested by the two harvesting machines, and the height of the remaining stump from the soil surface was measured with a simple ruler (accuracy 1 mm). We considered a height of 10 cm above the soil surface as the upper threshold. The biomass present between the 10 cm threshold and the realized cutting height was estimated using the stump height and the bulk density of the stump biomass. For the bulk density estimation 20 stumps of different diameters (from 20 mm to 60 mm) were manually cut by a handsaw in the field. The height and the diameter of the cut portion of the stump was measured with a digital caliper (accuracy 0.01 mm), and weighted with a precision balance (accuracy 0.01 g) after oven drying at 70 °C. The stump diameter and weight, for the bulk density estimation, were measured including the bark. Stump bulk density was estimated from the dry mass (DM) and the volume of the cylinder estimated from stump height and diameter. A linear allometric equation was established linking bulk density to stump diameter.

Using data of a diameter inventory of the entire plantation reported previously [27] and the allometric equation, an estimation of the average biomass per centimeter of stump height was made for the harvested field area. The estimated UB above the highest threshold (10 cm) was considered as biomass loss. Although the biomass cut below the lower threshold (7 cm) is a gain in the biomass yield, it was not considered as harvested biomass. Harvesting below the 7 cm was avoided because of the potentially negative impact on the resprouting [28].

To estimate the NRB, harvested woody debris and woody biomass material were collected from the soil surface on four areas of 1 m^2 within the land area harvested by each harvesting machine on the two genotypes (Skado and Koster). The collected biomass material and debris were brought to the laboratory and dried in a drying oven at 60-70 °C until constant weight. The NRB losses were expressed in g DM m^{-2}. Differences between harvesting machines were tested for the UB and the NRB with a one-way analysis of variance (ANOVA) and a Tukey post-hoc test ($p = 0.05$).

For the self-propelled cut-and-chip harvester we also performed a more refined analysis. The NRB was classified in stem and branches at one hand, and in woody chips on the other hand. The cut stem and branch biomass laying on the soil was considered as collection loss, i.e. the woody stem was cut, but the harvesting machine failed to collect the woody biomass to transport it into the chipping system of the machine. Chips biomass remaining on the soil after harvest was considered as a transfer loss from the harvester to the additional tractor–trailer combination (Fig. 1). For the tractor-pulled stem harvester only cut stems and branches were measured in the field.

The harvesting efficiency (Eff) of the harvesting machine was calculated as follows:

$$\mathrm{Eff}(\%) = \frac{\text{Potential harvestable biomass} - \text{NRB} - \text{UB}}{\text{Potential harvestable biomass}}$$

where potential harvestable biomass is the standing biomass above 7 cm at harvest. This potential harvestable biomass yield was calculated using the allometric equations previously developed and reported [29]. For these equations, 120 two-year-old trees were harvested by a handsaw in December 2011, before the mechanical harvest. The stumps were cut at 7 cm stem height, as this value was considered the lowest harvestable threshold by the harvesting machine. Potential harvestable biomass, NRB and UB were all expressed in g DM m^{-2}. Although we acknowledge that some water may stay in the biomass when it is dried at 70 °C, all the DM was obtained with the same methodology.

2.6. *Data collection at the onset of the next rotation*

After the harvest on 2–3 February 2012, the stumps started resprouting and produced new shoots from the end of March 2012 onward. Stump mortality was assessed in July 2012 – i.e. five months after the harvest – to evaluate the possible impact of the (two) harvesting machines on the resprouting success (i.e. coppice ability) of the poplars. The number of missing stumps in at least one complete single row per monoclonal block (i.e. between 70 and 330 stumps per row) were counted. A total of 34 rows and 4927 stumps were surveyed (approx. 2500 per harvesting machine). Stump mortality rates were calculated as the percentage (%) of dead stumps in relation to the number of stumps that were alive before the harvest. These latter ones were available from the detailed counting of summer 2011. We assumed that missing or dead stumps – since the counting in 2011 – were due to the harvesting operations. An overall mortality rate was calculated by combining all genotypes. A *T*-test was applied to evaluate whether the differences in the percentage of dead stumps were statistically different between the harvesting machines.

3. Results and discussion

3.1. *Harvest yield*

After two years of growth approximately 230 Mg of (fresh) woody chips were harvested from the 14.5 ha planted with trees. The mean dry mass yield was 8 Mg ha^{-1} for the two-year rotation, which was lower than the average values reported for SRWCs under European conditions [30]. The potential harvestable biomass calculated with the allometric relationship equation ranged from 468 g DM m^{-2}–1167 g DM m^{-2}. However productivity values of the first rotation period are generally lower than for subsequent rotations due to the early establishment from unrooted cuttings and the initial root development [31]. The moisture content on wet basis of the freshly harvested biomass was 50%. The chemical composition of the harvested SRWC chips from our plantation were reported earlier [32].

3.2. *Harvesting cost and machine productivities*

In this analysis we calculated the ownership and operation costs for the different harvesters, including labor costs, to estimate the (hourly) cost to own and operate the studied harvesters. Table 2 provides an overview of the calculated ownership and operation costs for the three harvesters and the accompanying tractor–trailer combination based on data collected from the harvest of our plantation. Table 2 also includes the productivity in tons per hour for each harvester. One should however take into account that this study was conducted on the first rotation of a very low-yield plantation (with a dry mass yield of approximately 4 Mg ha^{-1} y^{-1}). Therefore caution is required if the results are extrapolated to other sites or conditions. This caution also applies for the harvesting costs per oven-dried ton (odt) harvested biomass reported in the next paragraph.

The ownership and operation costs of the tractor-pulled cut-and-chip harvester of Ny Vraa – without considering the tractor–trailer combination to collect the chips – amounted to 83.6 € h^{-1}, excluding labor costs. This equaled a total harvesting cost, including the tractor–trailer combination and labor costs, of 387.7 € ha^{-1} or 48.5 € odt^{-1}, considering a yearly biomass increment of 4 odt ha^{-1} $year^{-1}$ and a rotation of 2 years. For the self-propelled cut-and-chip harvester of New Holland the ownership and operation costs equaled 212.5 € h^{-1}, whereas the harvesting costs amounted to

Table 3 – Potential harvestable biomass and not recovered biomass (NRB) of two harvesting machines. Observations on two clones (Skado and Koster) and two former land uses (cropland and pasture) after the harvesting campaign at the short rotation woody crop plantation field site. C = cropland, P = pasture.

Harvesting machine	Clone	Former land use	Potential harvestable biomass (g m^{-2})	NRB		
				n	(g m^{-2})	(%)
Self-propelled cut-and-chip harvester	Skado	C	1167	4	322.8	27.7%
	Skado	P	982	4	105.3	10.7%
Tractor-pulled whole stem harvester	Skado	P	982	4	35.3	3.6%
	Koster	C	468	4	14.3	3.0%
	Koster	P	657	4	2.1	0.3%

464.1 € ha^{-1} or 58.0 € odt^{-1}. For both the tractor-pulled cut-and-chip harvester and the self-propelled cut-and-chip harvester, the large differences between the hourly operation costs and the overall harvesting costs were due to the fact that these harvesting systems required an additional tractor–trailer combination (and driver) to collect the chips. Equipping these harvesters with an attached (and specially designed) trailer, however, would most probably decrease the total harvesting costs considerably. Unfortunately, a cost assessment of these scenarios was not possible, as these harvesters were not equipped with an attached trailer during the harvest at our operational plantation. So we were unable to record data regarding fuel consumptions and operation rates for these scenarios. The ownership and operation costs of the tractor-pulled stem harvester of Nordic Biomass amounted to 195.7 € h^{-1}, whereas the harvesting costs were 540.9 € ha^{-1} or 67.6 € odt^{-1}. Although the tractor-pulled stem harvester did not require an additional tractor–trailer combination (and driver) as the stems were collected in the machine's storage space, the total harvesting costs of this harvester were higher than the other two harvesters. This is mainly due to the high operation rate of the tractor-pulled stem harvester (Table 2). It is however important to mention that the stem harvester and the chip harvesters produce completely different products. Therefore, the harvesting costs of the stem harvester could not be straightforwardly compared with the other harvesters. The rods produced by the stem harvester still need to be chipped to deliver the same final product (i.e. woody biomass chips), which incurs additional costs. According to recent literature [15,24], post-harvest chipping costs vary between 15 and 20 € odt^{-1}, making the harvest-and-storage system even more expensive if woody biomass chips are to be delivered. At the POPFULL plantation approximately 95.4 Mg of fresh biomass (50% moisture content on wet basis) was chipped at a costs 1.035 €, corresponding to a cost of 21.68 € odt^{-1}. In spite of its financial drawbacks, this harvesting system has the advantage to let the biomass air-dry on the field (no need for extra storage space) until it reaches the required moisture content before chipping the material. This increases the quality of the biomass delivered and as a consequence the price of the biomass chips. At our plantation, however, the rods were chipped on site right after harvesting.

3.3. *Efficiency of the harvesting machines*

The harvest loss analysis was done without including the tractor-pulled cut-and-chip harvester, because this harvester was not able to harvest the larger (poplar) trees. In December 2011 the mean stem diameter (measured at a height of 22 cm) was 40.8 mm (±0.16, $n = 4928$) for poplars and 24.3 mm (±0.42, $n = 289$) for willows. Although a cutting height of 7–10 cm had been requested at the start of the harvest, the realized stem cutting height was 15.46 cm and 16.00 cm for the tractor-pulled stem harvester and the self-propelled cut-and-chip harvester, respectively (Table 4). As a result, an average of 5.5 cm and 6.0 cm of woody stem – per individual harvested stem –was lost as it remained on the field. None of the harvesting machines cut below the lower threshold (7 cm). No statistically significant differences were found between the two harvesting machines, but the tractor-pulled stem harvester had a more variable cut height than the self-propelled cut-and-chip harvester (Fig. 5). Based on the established allometric relations, the UB averaged 37.2 g DM m^{-2}. This value was much lower than the UB reported for switchgrass, which accounted for 400 g DM m^{-2} [26]. On average 6.5 g DM m^{-2} (i.e. 65 kg ha^{-1}) of biomass was lost for every

Table 4 – Comparative results of the performance of two harvesting machines based on the observations after the harvesting campaign at the short rotation woody crop plantation field site. Data only refer to poplar.

Harvesting machine	Tractor-pulled whole stem harvester	Self-propelled cut-and-chip harvester	Approach, source
Mortality after harvest (%)	0.68	0.54	Observations 5 months after harvest
Not recovered biomass (g DM m^{-2})	35.3	105.3	Left-overs quantified at field site on the same clone (Skado)
Harvesting height (cm)	15.46	16.00	Measured at field site
Efficiency (%)	93.4	68.7	Potentially harvestable biomass, uncut biomass and not recovered biomass

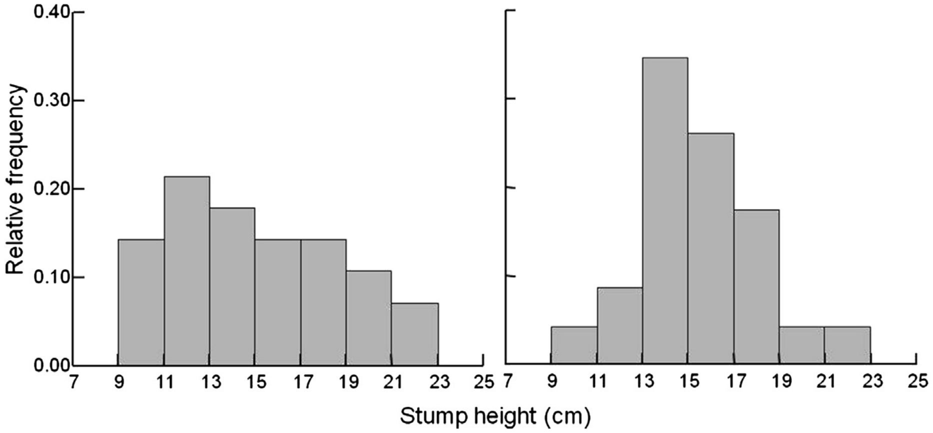

Fig. 5 – Relative frequency of the stump height above the soil (cutting height) for the tractor-pulled whole stem harvester (left panel) and the self-propelled cut-and-chip harvester (right panel).

centimeter of stem height that we harvested above the threshold height in our two-year-old trees. The attainable cutting height should be minimal to harvest as much material as possible. The lower the cutting height, however, the more contamination with soil particles among the wood chips might occur.

On average, losses by NRB accounted for 17.2 g DM m^{-2} for the tractor-pulled stem harvester versus 214.0 g DM m^{-2} for the self-propelled cut-and-chip harvester (Table 3). In the self-propelled cut-and-chip harvester, NRB losses consisted of 97.2 g DM m^{-2} front losses of cut biomass that the machine failed to chip, and 116.8 g DM m^{-2} of biomass chips lost during the transfer from the harvester to the tractor–trailer combination. In analogy with grain crops, front losses are linked to the design of the cutting table and the mode of operation of the harvester [34]. The high front losses found in the self-propelled harvesting machine could be due to the relatively low harvesting or operation rate of the harvesting machine during the operation (Table 2). There might also be chip losses during the chipping of the rods harvested by the stem harvester. But this chipping process can be operated on a concrete floor and the lost chips recovered afterwards.

Considering all the losses, only 77.4% of the potentially harvestable biomass was harvested on average by the self-propelled cut-and-chip harvester, while the tractor-pulled stem harvester collected 94.5% of the potentially harvestable biomass (Table 4). In terms of losses, the UB accounted for ca. 3.6% of the biomass for both harvesting machines. Under the same conditions (clone: Skado and land: pasture), the NRB differed between both harvesting machines; it accounted for 3.6% and 10.7% for the tractor-pulled stem harvester and the self-propelled cut-and-chip harvesting machine, respectively. There was no clear relation between potential harvestable biomass and NRB (Table 3). As far as we know, losses after harvest of SRWC poplars and willows have never been carefully quantified or assessed. A harvest efficiency of 64% of the potentially harvestable biomass has been reported for switchgrass [26]. As machinery costs – and harvest machinery in particular – represent the highest input costs for biomass production (Silveira [33] cited in Hannum [12]) the harvest efficiency should be increased to reduce overall costs and increase the competition of biomass with other energy sources.

The overall mortality rate, expressed as the percentage (%) of dead stumps, after harvesting was very low (i.e. less than

Table 5 – General comparison of the three studied harvesting systems.

	Self-propelled cut-and-chip harvester	Tractor-pulled cut-and-chip harvester	Tractor-pulled whole stem harvester
Collection of biomass	Additional tractor–trailer combination required	Additional tractor–trailer combination required – Trailer attached to the same tractor in option	Trailer attached to the same tractor
Compaction of the soil	High (if not frozen)	Low (if on tracks)	Moderate (if on tracks)
Maximum diameter (cm)	15	4–6	15–20
Final product	Biomass chips (10–45 mm)	Biomass chips (5–30 mm)	Whole stems/rods (additional chipping required)
Availability in Belgium	Available	Not available	Not available
Storage capacity	Dependent on the trailer	Dependent on the trailer	Max. 5 Mg
Access to the field	Able to harvest any plantation design	Pre-designed plantation scheme required	Pre-designed plantation scheme required

1%) as shown by the successful resprouts (Table 4). A *T*-test showed that differences between both harvesting machines were not significant ($P < 0.05$). High reductions in the number of stems produced due to mechanical damage have been reported for willow plantations, but damaged plants compensated by producing larger stems [35]. In our study, mechanical damage was not a major problem for the resprouting success.

A number of additional pro's and con's could be considered when selecting the appropriate harvesting system or machine for the harvest of SRWCs (Table 5). The side harvesting machine requires a pre-designed plantation scheme (Fig. 6), as it needs an empty row or a previously cut row where the tractor can drive. In contrast, a front harvesting machine can start the harvest operation in any row of the plantation. The stem harvester was not able to harvest the long rows before the storage capacity was reached; for rows with a length of more than 200 m a cut-and-chip harvester was needed. According to the manufacturer, this machine is also able to harvest longer rows if accompanied by a shuttle wagon. Although we did not quantify the differential impact of the harvesters on the soil, a recent comparative study showed that various forest harvesters had a different impact on soil compaction and changed soil density accordingly [35,36]. Lighter machines with wide tire dimensions are recommended to decrease soil contact pressure. Most of the advantages and disadvantages of the operated machines are summarized in Table 5.

Given a number of limitations of our study, caution is required if the results are extrapolated to other sites or conditions. Firstly, this study was conducted on the first rotation of a very low-yield plantation. Secondly, we did not specifically design the study for the harvest test. However, very few studies have been conducted on a comparison of different commercial harvesters at a plantation of this size (14.5 ha).

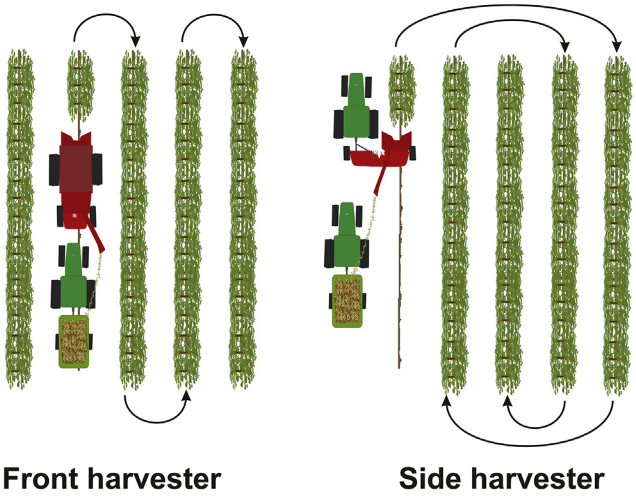

Fig. 6 – Representation of the turnings for a front harvesting machine and for a side harvesting machine. The front harvesting machine can start to harvest in any row of the plantation and turn to any row. The side harvest machine needs an empty row or a harvested row where the tractor pulling the machine can drive. This results in longer turnings.

4. Conclusion

In conclusion, this study confirmed that harvesting machines have their specific advantages and disadvantages. The harvesting machines that we evaluated differed in their operational cost (e.g. one-step operation vs. two-steps operation), their harvest capacity (i.e. stem diameter, row length), their harvest efficiency (i.e. losses) and the final product (chips or rods). In the selection of the appropriate harvesting machine, speed performance should be the second priority; the first priorities should be the success of the resprout, the efficiency of the harvesting process and the quality of the final product. To minimize the impact on the soil light-weighted machines are to be preferred.

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