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Operational short rotation woody crop plantations: manual or mechanised harvesting?

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Abstract

Harvesting is the most expensive, but the least investigated process in the cultivation of short rotation woody crops (SRWC). To get a better idea of the harvesting process (in terms of its performance, productivity, cost, soil compaction, cutting height and quality as well as biomass losses), we closely monitored the second harvest of a SRWC culture in Flanders (Belgium). We compared our results to the harvests of other, small European parcels. The trees at our site were harvested with both a manual and a mechanised (Stemster harvester) cut-and-store system, while the cut-and-chip system was analysed from an extensive literature survey. The production cost (to the edge of the field) at our site reached 426 (manual) and 94 (mechanised) € t^{-1}, while the average values found in the literature are respectively 104 and 78 € t^{-1}, versus 17 € t^{-1} for the cut-and-chip harvesting system. The productivity at our site reached 14 (manual) and 22 (mechanised) oven-dry tonnes per scheduled machine hour, while the average values found in the literature are respectively 15 and 23 t h^{-1}. Based on the good performance (ha h^{-1}) and productivity (t h^{-1}) of the cut-and-chip system as well as its lower costs, this harvesting system is recommended for operational SRWC.

Keywords

POPFULL, wood chips, poplar, harvesting efficiency, motor-manual harvesting.

1. Introduction

In the light of the EU's target to obtain a 20% overall share of energy from sustainable sources [1], biomass is considered being one of the most interesting options to generate renewable energy [2]. Short rotation woody crops (SRWC) are very suitable for the efficient production of biomass [3, 4]. The fast growth, the high yield and the availability of disease resistant genotypes make poplars (*Populus* spp.) and willows (*Salix* spp.) ideal species for SRWC [5-8]. Within the SRWC cultivation method, trees are harvested every 2-5 years over a total period of 20-30 years [9].

Extensive research has already been performed on various aspects of SRWC as: the selection of suitable species and genotypes [10, 11]; the influence of regular coppicing [10, 12]; the duration and frequency of rotation cycles [5, 13]; management issues related to planting, weeding [14], pesticide application, irrigation [15, 16]; etc. Although detailed information about the harvesting procedure of SRWC is crucial, it is still not possible for a farmer to estimate the expected harvesting costs in advance. Especially the costs and the effectiveness of different harvesting systems and techniques need to be more thoroughly investigated as the harvesting operation is one of the most expensive processes along the entire production chain [17, 18]. The lack of knowledge on harvesting [19] and the uncertainties regarding the expected costs and profits [20, 21] are the main reasons why farmers hesitate to establish SRWC [9, 22].

The main aim of this study was to provide harvesting costs, productivity figures and performance indicators (incl. soil compaction, cutting height and quality as well as biomass losses) for a fully mechanised and a motor-manual harvest of an operational SRWC plantation. To evaluate our results and to make recommendations to farmers, a literature review providing information about productivities, costs and/or performance indicators of different harvesting systems was also carried out.

State of the art

In general, two different harvesting systems are used for SRWC: the cut-and-store and the cut-and-chip system. The plantations that were reviewed from the literature all appeared to be small scale; the largest SRWC plantations taken into account were 2.46 ha [23] and 21.89 ha [24], respectively, for manual and mechanised harvesting operations.

{Insert Figure 1 here}

The cut-and-store harvesting system is a two-step operation: (i) harvesting the entire shoot, and (ii) hauling and chipping the cut stems to the edge of the field [25, 26]. The harvesting can be done manually or mechanised. Respectively 11 (manual) and five (mechanised) field studies from Germany were retrieved from the literature (Appendix 1, summarised in Table 1). Manual harvesting of SRWC has been analysed since many years [31, 32]. It is very labour intensive and is only of interest if a mechanised system is not available or not possible (e.g. due to the small dimensions of the field, weather and/or soil conditions, etc.). Usually a chainsaw is used, although some studies report a bow or brush saw [32]. The harvesting is generally carried out by a team of two labour forces: one person cuts the trees while the other pushes them into the desired direction or pre-piles the cut trees to facilitate the subsequent (mechanised) forwarding process [27]. Mechanised harvesting operations are done by using a specialised harvesting head attached to an agricultural vehicle (e.g. the Stemster harvester [33]). Manual and mechanised harvesting reach average productivities of 1.23 (± 0.60) t h^{-1} (manual) and 9.50 (± 1.47) t h^{-1} (mechanised). The harvesting costs vary from 22.65 (± 14.20) € t^{-1} (manual) to 18.54 (± 4.16) € t^{-1} (mechanised) (Table 1). Only metric oven-dry tonnes are used throughout this manuscript, unless otherwise stated.

Hauling is a necessary working step after harvesting because typically the trees are stored for a prolonged period which might inhibit the resprouting of the stumps when left in the field. Usually the stems are transported over small distances (100-200 m) and concentrated on the headlands of the fields to wind-dry in bulk. In the literature, six field studies from Germany and two from Italy were retrieved; they processed on average 5.34 (± 3.06) t h^{-1} at 33.34 (± 30.65) € t^{-1} (Appendix 2, summarised in Table 1). Chipping can be postponed either according to the demand or to the required heating value. After several months of drying, a reduced moisture content of ca. 20–25% can be reached, resulting in an increased heating value of ca. 12 GJ t^{-1} [36, 37]. As a result, upgraded chips with higher revenues can be expected and no additional investment, space or time for drying or storage of chips are needed. Twelve studies from Germany and four from Italy were found in the literature, which processed on average 8.19 (± 4.44) t h^{-1} at 26.49 (± 7.92) € t^{-1} (Appendix 2, summarised in Table 1). The overall average productivities of the manual and the mechanised cut-and-store system are respectively 15 and 23 t smh^{-1}, at 82 and 78 € t^{-1} (Table 1).

{Insert Table 1 here}

The cut-and-chip harvesting system is a one-step operation converting standing biomass into woody chips. In this harvesting system stems are usually pushed into a horizontal position before entering the cutting head of the harvester; however, vertical feeding of the cutting head is also possible [17]. The cutting head is a specialised woody biomass cutting head attached to a powerful modified forage harvester, or a mower-feeder cutting head attached to a less powerful standard agricultural tractor [38]. The chips are immediately blown into an accompanying tractor-pulled trailer, which drives by the side of the harvesting machine and transports the chips to the storage facility [39, 40]. Produced woody chips have a low lower heating value (ca. 7-10 GJ t^{-1}), because they have a moisture content of ca. 50-60%. These chips can be dried in an oven or immediately stored at a high moisture content to allow slow natural drying. However, this storage is problematic as it will cause mass losses and fungal emissions, due to increased temperatures and microbial activity [36, 41, 42]. The harvested amount and the farmer's opportunities for drying and storing are other constraints; therefore, immediate use is advisable. In the literature, one study from Germany, four from Italy, one from Sweden and one from Switzerland were found, totalling 25 different field studies [24, 35, 43-45]. On average, these studies yielded 15.93 (± 6.78) t h^{-1}, at 17.69 (± 5.70) € t^{-1} (Appendix 1, summarised in Table 1).

2. Materials and Methods

2.1 The POPFULL experimental field site

The harvesting trials as well as all measurements were carried out on the operational POPFULL plantation [46], located in Lochristi, Belgium (51°06'44" N, 3°51'02" E). The soil of the site is sandy and has a poor natural drainage due to a clay-enriched layer below 60 cm [8]. The total area was 18.40 ha from which 14.76 ha were planted in 2010 with 12 different poplar (*Populus*) and 3 different willow (*Salix*) genotypes, all commercially available. The poplar genotypes represented four parentages and included pure species and hybrids of *Populus deltoides*, *P. maximowiczii*, *P. nigra* and *P. trichocarpa* [8]. The willow genotypes included one pure species and hybrids of *Salix viminalis*, *S. dasyclados*, *S. alba* and *S. schwerinii*. All genotypes were planted as large monoclonal blocks in a double-row planting scheme: the narrow and the wide rows were respectively 75 and 150 cm wide, and the distance between trees within a row was 110 cm. An overall planting density of 8,000 trees per ha was achieved, totalling 118,400 trees. Chemical, mechanical and manual weeding was performed during the first growing season after planting, and herbicides were applied a second time after the first harvest in 2012. Neither irrigation nor fertilization was ever applied since the start-up. More information on the site, its establishment, planting material, soil conditions and management has been previously published [8]. At the time of harvest, there were on average 10.07 ± 5.15 shoots per stump, with an average diameter of 18.59 ± 14.50 mm [47].

2.2 Harvesting operations at the plantation

After trees had been growing for two years in the second rotation (2012-2013), the POPFULL plantation was harvested between 18 and 21 February, 2014. Because of the mild 2013-2014 winter conditions, the soil was not frozen. Therefore only light-weight harvesting machines on caterpillars were able to access the field and were used in order to minimize soil compaction. In studies 1, 2 and 3, we evaluated three cut-and-store harvesting systems at the plantation; each of them harvested different fractions of the entire plantation.

Study 1. The largest part of the plantation (13.28 ha) was harvested using the Stemster harvester. This is a side-operated, tractor-pulled harvester that consists of a tractor (JD 6920, Deere & Company, USA) and a harvest-trailer combination (Stemster MKIII, Nordic Biomass a/s, Denmark), both on caterpillars (Table 2) [33]. The operator was a professional and experienced driver. Because the Stemster is a side operator, it was facilitated by motor-manual harvesting of a selection of rows, a grabbing crane and a forest cutter (discussed as study 2). The grabbing crane and the forest cutter were both attached to a forwarder (type CAT 314 D, Caterpillar Inc., USA) on caterpillars and operated by experienced drivers.

Study 2. An area of 1.36 ha was harvested motor-manually by a team of two workers. The manual harvesting was carried out using chainsaws (364XP, 357XP and T435, Husqvarna AB, Sweden; and MS 201T, Andreas Stihl AG & Company, Germany). The chainsaws were exclusively operated by the team leader.

Study 3. A very small part (0.12 ha) of the plantation was harvested using the GMT035 (Gierkink Machine Techniek, The Netherlands) harvester, a forest harvesting head used in traditional forestry [48]. This harvesting head was attached to a JD 1110E (Deere & Company, USA) tractor-trailer combination (Table 2), operated by an experienced driver. No time study was conducted on this machine due to the small area harvested; the harvesting head was evaluated as not suitable for SRWC harvesting and therefore not used further.

{Insert Table 2 here}

All hauling operations were carried out using the CAT 314 D machine (as described under study 1). Trees were hauled 100-330 m to the edge of the field, where chipping was carried out using the Komptech 510C (Komptech GmbH, Austria) machine in combination with a Fendt 936 tractor (ACCO GmbH, Germany).

2.3 Data collection and analysis

We carried out time-motion studies [49] during two out of three harvesting operations, i.e. the Stemster and the motor-manual harvesting operation, which were both done by external contractors. We monitored the Stemster harvest (study 1) for 8.6 h and the motor-manual harvest (study 2) for 13.3 h, at different intervals of at least 1 h during their scheduled activity. The duration of the machine assembly before the harvest and the maintenance afterwards were also taken into account. All times were recorded using a stopwatch with an accuracy of 1 s. For the data collection of both time studies (study 1 and study 2), the harvesting process was split into the following working steps with clearly recognizable starting and ending points. In study 1: harvesting; transport between rows; offloading of the cut stems (when the carrying capacity of the trailer is reached); personal and operational delays. In study 2: harvesting; pre-piling of cut stems; personal and operational delays.

In study 2, both labour men were monitored simultaneously. Because the time periods used for maintenance and delays encountered during the harvesting operation were not representatively monitored, the responsible operators were asked to report the time spent on maintenance (including fuelling) and personal delays (e.g. lunch, phoning, resting). The scheduled machine hours were defined as the time invoiced by both companies and they were distinguished from the productive machine hours by subtracting the unmonitored time elements.

For both harvesting operations, the exact harvested area was calculated using ArcGIS 9.3 [50]. The amount of harvested biomass (green tonne) was directly measured in situ with a specific gravity balance by the Stemster (with an error of 5-10% [51]). This value was converted to oven-dry tonnes by weighing two randomly selected stems wet and dried (at 70 °C until constant weight). The stocking biomass (t ha^{-1}) was obtained by dividing the total amount of oven-dry tonnes by the planted area. We assumed that the stocking biomass was equal at every part of the plantation, and therefore for all three harvest methods. We calculated the amount of hours needed to harvest one hectare (h ha^{-1}) and the amount of oven-dry tonnes harvested per hour (t h^{-1}). Furthermore, we calculated the total harvesting costs per hour, per hectare and per oven-dry tonne (€ h^{-1}, € ha^{-1}, € t^{-1}). All labour was outsourced at 55 € h^{-1} and fuel costs were included at a rate of 1.452 € l^{-1} for diesel [52] and 3.26 € l^{-1} for two-stroke fuel. The latter was the price we had to pay to the contractor.

After the harvest we assessed the impact of the Stemster harvester on soil compaction through measurements of the pressure needed to penetrate the soil with a penetrologger (Eijkelkamp type 06.15.SA, The Netherlands). The procedure as described in the instrument manual was followed with a 1 cm^2 cone surface area. As an output, a graph was generated, showing a pressure profile with depth. We randomly measured 16 transects before and 20 transects after the harvest with eight sampling points in each transect, equally spread over monoclonal blocks of two genotypes, i.e. Skado (*P. trichocarpa* x *P. maximowiczii*) and Koster (*P. deltoides* x *P. nigra*). From the eight sampling points, points 1-3 were located in and averaged as a measure for the narrow row, as was done for points 4-8 for the wide row (Figure 2). The wide rows are used for transit of agricultural vehicles (e.g. the Stemster harvester) and the narrow rows can be seen as control rows. Measurements before *vs.* after the harvest, and narrow *vs*. wide rows, were averaged, resulting in four curves: before the harvest in the narrow *vs.* the wide row and after the harvest in the narrow *vs.* the wide row. Per cm of depth, the Welch two sample t-test was used to test if differences between these four curves were significant. Analyses were performed using the R software [53].

{Insert Figure 2 here}

Beside soil compaction we quantified the cutting height as well as the quality of the cut in all three harvesting operations (Stemster, manual and GMT035 harvest). We asked all operators to cut at a height of 7-10 cm above the ground level. After harvesting, we measured the height of a random selection of stumps (between 32 and 100) per genotype and per harvest operation. P-values were generated with a Welch two sample t-test in R [53]. We visually inspected the quality of the cut and the resprouting success of all trees for each harvesting method in order to subjectively asses the quality of the harvesting operations.

Biomass losses which occurred during the harvesting operation were quantified by collecting the left biomass on eight randomly selected quadrants of 0.36 m^2 each [54, 55]. These quadrants were equally distributed over the genotypes Skado and Koster, i.e. four replicates per clone. For each quadrant, we collected all woody biomass left both cut and uncut pieces. When stems crossed the quadrants' boundaries, they were cut as to only collect the parts that were confined within the limits of the quadrants. All samples were oven dried at 70°C until constant weight to estimate their biomass.

As a quality parameter of the product, we monitored the effect of wind-drying on wood moisture content. Two freshly cut stems dried till 16 April 2014 (54 days) and two stems dried till 04 June 2014 (103 days) were randomly collected from a pile of stems. Stems were collected from the middle of the pile, to avoid border effects. Piles were kept at the edge of the field; they were 3-4 m high, with variable widths. Samples were weighed (accuracy 0.01 g), oven dried (at 70 °C) until constant weight, and weighed again to calculate the moisture content.

3. Results

In total we harvested 351 t of biomass at the second harvest after the second two-year rotation cycle, equalling an above-ground biomass yield of 11.9 t ha^{-1} yr^{-1} during the second rotation. The manual harvesting operation, the Stemster harvester and the GMT035 machine harvester, yielded respectively, 32, 316 and 3 t. The detailed time measurements (Figure 3) showed that 76 and 94% of the scheduled machine hours were occupied by productive machine hours with the Stemster and the manual harvesting, respectively. The major reasons for the smaller share of productive machine hours of the Stemster harvester were the time required for the (dis)assembly and the longer maintenance times. The difference in the productive machine hours between the harvesting operations was explained by the time needed – by the Stemster – for turning between the rows, whereas the manual harvesting could continue without (major) interruptions. The share of personal delays was very small in the manual harvesting operation (3%) as the harvested area was relatively small.

{Insert Figure 3 here}

Our experimental data (Table 3) showed that the manual harvesting operation was performed much slower than the mechanised harvesting (0.01 *vs.* 0.37 ha h^{-1}), resulting in a lower productivity (0.15 *vs.* 8.84 t h^{-1}). The literature data (Table 1) confirm these findings and further show that the one-step cut-and-chip harvesting is intermediate in terms of performance and productivity as compared to both cut-and-store harvesting systems. Also the costs associated with the harvest operations at our POPFULL plantation were confirmed by findings in the literature: the cost per hour was lower for the manual cut-and-store method as compared to the mechanised cut-and-store method (440 *vs.* 674 € h^{-1}), and this did not compensate for the higher cost per hectare and tonne (10142 *vs*. 2232 € ha^{-1} and 426 *vs.* 94 € t^{-1}). Most costs associated with manual harvesting were due to machine breakdowns caused by sawing close to the ground (whereby a lot of sand and dirt blocked the chain) and by the high number of revolutions of the chainsaw engine (the small diameter of the trees did not provide much resistance). Furthermore, the literature shows that the cut-and-chip harvesting system is the cheapest option per scheduled machine hour (244 ± 95 € h^{-1}), per hectare (500 ± 205 € ha^{-1}) and per tonne (18 ± 6 € t^{-1}).

The penetrometer results up to 38 cm depth (Figure 4) showed that there was a significant difference in compaction between the narrow and the wide rows. The narrow rows were significantly less compacted than the wide rows ($p < 0.001$ from 2-38 cm deep), but there was no significant difference before and after the harvest ($p > 0.3$). Therefore, the difference between narrow and wide rows was not caused by the harvest operation of February 2014. Soil compaction data below 38 cm contained too much noise for a clear picture due to irregularities in soil characteristics (*e.g.* stones and water table) and missing data with increasing depth.

{Insert Figure 4 here}

The average harvest height of the manual harvesting operation, for the Stemster and the GMT035 machines was 9.09 (± 3.31) cm, 10.11 (± 2.73) cm and 9.24 (± 2.91) cm, respectively. This was within the requested upper limit of 10 cm. The difference between the harvest heights of the manual harvesting and the mechanised harvesting system using the Stemster was significant ($p < 0.01$). The difference between the Stemster and the GMT035 harvesting machines was also significant ($p < 0.01$). All three harvesting methods were visually examined for the quality of their cut. This cutting area had a smooth surface after all three harvesting methods (Figure 5), which was, however, degraded by the forwarder accompanying the GMT035 harvester. The resprouts of the area harvested by the GMT035 could not be inspected as this part of the plantation was converted into maize cultivation immediately after the harvesting. The timing of the resprouting was subjectively and visually monitored every week on the areas harvested manually and with the Stemster. Results were comparable; all stumps started vigorously producing resprouts around May 2014. The total stocking biomass was 24.90 t ha^{-1}, from which 4% (i.e.

1.12 t ha^{-1}) were lost during the harvesting operations. The moisture content of the freshly cut stems was on average 56%, which dropped to 53% after 54 days of natural wind-drying, and further dropped to 42% after 103 days of natural wind-drying of the piles of harvested stems.

{Insert Figure 5 here}

4. Discussion

When interpreting results retrieved from the literature, it should be taken into account that about one third of all studies examined the first harvesting operation only, i.e. before plantations developed a real “coppice culture”. Studying the differences in harvest efficiency between a first and a later harvest of SRWC would be an interesting question to address in future studies. A second noteworthy remark is that almost all available literature studies were performed in Germany and Italy. This should be taken into account when (i) comparing costs to Belgium, where labour costs are higher; and (ii) extrapolating costs to other countries with different wages.

The low cost per hour of the manual harvesting operation (338 € h^{-1}) compared to the cut-and-store system using the Stemster harvester (640 € h^{-1}) and the cut-and-chip system using a forage harvester (244 € h^{-1}) did not compensate for the difference in performance and productivity of both systems. Therefore, the cut-and-chip system is considered to be the cheapest way of harvesting SRWC, followed by the Stemster harvester and the manual harvesting. When rotation length is increased to 10 years, however, manual harvesting might become economically competitive with fully mechanised harvesting per tonne [56]. The passive reduction of the wood moisture content from 56 to 42% should be able to drop to < 30% and leads to high quality biomass without the need for special techniques, and is therefore an interesting process for small-scale SRWC managers [56].

An important issue to be addressed is the influence of the plantation design. At the establishment of our POPFULL site, the harvest was taken into account (headlands were foreseen), but no specific harvesting system was anticipated. Preparing the design for one particular harvester was not feasible because of the operational and technological unpredictability of future harvests [18]. An optimal design, mainly characterized by minimum 12 m wide headlands (currently 8 m wide), would reduce the Stemster harvester's time needed for turning between the different rows [18]. The disadvantage would be a reduced planting area, which is considered to be minimally 300 ha for an economically efficient, mechanised harvest (with forage harvesters) [17]. The loss of 4% of the potential yield caused by the harvesting operation was comparable to the 5.5-8% reported in the literature [18, 55].

In conclusion, we propose to use a cut-and-chip system for harvesting areas of 1 ha. This method proofs to be the cheapest per hour, per hectare and per tonne, although it is not the fastest performer (ha h^{-1}) and does not have the highest productivity (t h^{-1}). When field conditions or logistic arrangements do not allow the use of an integrated cut-and-chip harvester, the mechanised harvesting (with the Stemster) is the second best option. It comes at a high cost per hour, but this is compensated by its much higher performance and productivity, resulting in a lower cost per hectare and lower cost per tonne. The least beneficial harvesting method for small SRWC parcels is the manual harvesting, because it produces chips at a high cost due to its low performance and productivity.

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6. References

[1] Commission of the European Community. 20 20 by 2020, Europe's climate change opportunity. Communication from the Commission to the European Council and the European Parliament (2008/30). Brussels; 2008.

[2] Commission of the European Community. Renewable energy road map. Renewable energies in the 21th century: building a more sustainable future. Communication from the Commission to the European Council and the European Parliament (2006/848). Brussels; 2007.

[3] Ceulemans R, Scarascia-Mugnozza G, Wiard BM, Braatne JH, Hinckley TM, Stettler RF, et al. Production physiology and morphology of *Populus* species and their hybrids grown under short rotation. 1. Clonal comparisons of 4-year growth and phenology. Canadian Journal of Forest Research 1992;22(12): 1937-1948.

[4] Bentsen NS, Felby C. Biomass for energy in the European Union - a review of bioenergy resource assessments. Biotechnology for Biofuels 2012;5(25).

[5] Al Afas N, Marron N, Van Dongen S, Laureysens I, Ceulemans R. Dynamics of biomass production in a poplar coppice culture over three rotations (11 years). Forest Ecology and Management 2008;255(5-6): 1883-1891.

[6] Njakou Djomo S, El Kasmioui O, Ceulemans R. Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. Global Change Biology Bioenergy 2011;3(3): 181-197.

[7] Aylott MJ, Casella E, Tubby I, Street NR, Smith P, Taylor G. Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK. New Phytologist 2008;178: 358-370.

[8] Broeckx LS, Verlinden MS, Ceulemans R. Establishment and two-year growth of a bio-energy plantation with fast-growing *Populus* trees in Flanders (Belgium): Effects of genotype and former land use. Biomass & Bioenergy 2012;42: 151-163.

[9] Schweier J, Becker G. Harvesting of short rotation coppice - Harvesting trials with a cut and storage system in Germany. Silva Fennica 2012;46: 287-299.

[10] Dillen SY, El Kasmioui O, Marron N, Calfapietra C, Ceulemans R. Chapter 14: Poplar. In: Halford N, Karp A, editors. Energy crops. Cambridge, UK: Royal Society of Chemistry; 2011, pp. 275.

[11] Willebrand E, Ledin S, Verwijst T. Willow coppice systems in short-rotation forestry - effects of plant spacing, rotation length and clonal composition on biomass production. Biomass & Bioenergy 1993;4:323-331.

[12] Verwijst T. Thematic introduction to short rotation forestry, short rotation coppice and energy grasses. In: Dallemand JF, Petersen JE, Karp A, editors. Proceedings of the Expert Consultation: "Short rotation forestry, short rotation coppice and perennial grasses in the European Union: Agro-environmental aspects, present use and perspectives". Harpenden, United Kingdom: European Commission Joint Research Centre - Institute for Energy, ; 2007, pp. 9.

[13] Herve C, Ceulemans R. Short-rotation coppiced vs non-coppiced poplar: a comparative study at two different field sites. Biomass & Bioenergy 1996;11:139-150.

[14] Welham C, Van Rees K, Seely B, Kimmins H. Projected long-term productivity in Saskatchewan hybrid poplar plantations: weed competition and fertilizer effects. Canadian Journal of Forest Research 2007;37:356-370.

[15] Linder S, Rook DA. Effects of mineral nutrition on carbon dioxide exchange and partitioning of carbon in trees. In: Bowen GD, Nambiar EKS, editors. Nutrition of Plantation Forests. London, UK: Academic Press; 1984, pp. 211.

[16] Ibrahim L, Proe MF, Cameron AD. Interactive effects of nitrogen and water availabilities on gas exchange and whole-plant carbon allocation in poplar. Tree Physiology 1998;18:481-487.

[17] Pecenka R, Ehlert D, Lenz H. Efficient harvest lines for short rotation coppices (SRC) in agriculture and agroforestry. Agronomy Research 2014;12: 151-160.

[18] Eisenbies MH, Volk TA, Posselius J, Foster C, Shi S, Karapetyan S. Evaluation of a single-pass, cut and chip harvest system on commercial-scale, short-rotation shrub willow biomass crops. BioEnergy Research 2014:1-13.

[19] Sherrington C, Bartley J, Moran D. Farm-level constraints on the domestic supply of perennial energy crops in the UK. Energy Policy 2008;36: 2504-2512.

[20] El Kasmioui O, Ceulemans R. Financial analysis of the cultivation of poplar and willow for bioenergy. Biomass & Bioenergy 2012;43:52-64.

[21] El Kasmioui O, Ceulemans R. Financial analysis of the cultivation of short rotation woody crops for bioenergy in Belgium: barriers and opportunities. Bioenergy Research 2013;6: 336-350.

[22] Schweier J, Becker G. Economics of poplar short rotation coppice plantations on marginal land in Germany. Biomass & Bioenergy 2013;59-494.

[23] Burger FJ. Bewirtschaftung und Ökobilanzierung von Kurzumtriebsplantagen (Cultivation and life cycle assessment of short rotation coppice). Lehrstuhl für Holzkunde und Holztechnik: Technische Universität München; 2010, p. 180.

[24] Fiala M, Bacenetti J. Economic, energetic and environmental impact in short rotation coppice harvesting operations. Biomass & Bioenergy 2012;42:107-113.

[25] Gigler JK, van Loon WKP, van den Berg JV, Sonneveld C, Meerdink G. Natural wind drying of willow stems. Biomass & Bioenergy 2000;19:153-163.

[26] Eriksson L, Gustavsson L. Comparative analysis of wood chips and bundles - Costs, carbon dioxide emissions, dry matter losses and allergic reactions. Biomass & Bioenergy 2010;34:82-90.

[27] Schweier J, Becker G. Motor manual harvest of short rotation coppice in South-West Germany. Allgemeine Forst Und Jagdzeitung 2012;183: 159-167.

[28] Nahm M, Brodbeck F, Sauter UH. Verschiedene Erntemethoden für Kurzumtriebsplantagen (Different harvesting methods for short rotation coppice): Forest Research Institute Baden-Württemberg; 2012.

[29] Schneider I. Statusbericht „Praxisversuch Energieproduktion und -verwertung“. Bewirtschaftung, ernte und verwertung von pappel- und weiden in kurzumtrieb (Status report „field trial energy production and –use“. Cultivation, harvest and use of poplars and willows in short rotation). Baden-Württemberg: Forest Research Institute; 1995.

[30] Mayer B. Praxisversuch Energieproduktion und -verwertung. Ernte und Rekultivierung von Pappel- und Weiden-Niederwäldern im Kurzumtrieb. Teil II (field trials energy production and -use. Harvesting and recultivation of poplar and willow coppice in short rotation. Part II). Forest Research Institute Baden-Württemberg; 1996, p. 21.

[31] Löffler H, Patzak W, Dürrstein H. Ernte in Kurzumtriebsplantagen (Harvest in short rotation coppice). Holz-Zentralblatt 1988;61:958 (in German).

[32] Küppers J-G, Schweinle J, Thoroe C, Wipperman H-J. Betriebswirtschaftliche und erntetechnische Begleitforschung zum Anbau schnellwachsender Baumarten auf landwirtschaftlichen Flächen (Economic and harvest research regarding the cultivation of fast growing tree species on agricultural lands).

Hamburg: Institute of economy. Federal Research Centre for Forestry and Forest Products; 1997, p. 87 (in German).

[33] New Nordic Biomass a/s. Stemster MK III specifications. Taars (DE). [Updated 2011; cited 2014 March 3] Available from http://www.nordicbiomass.dk/files/nbnewfiles/Technical%20data%20NB%20STEMSTER%20III.pdf. Hvidstedvej 75, DK-9830 Taars, Denmark. pp. 4; 2011.

[34] Heinrich N. Ernte und Logistik von Holz aus Kurzumtriebsplantagen -Verfahrenstechnische Optimierungsansätze (Harvest and logistic of wood from short rotation coppice- procedural approaches for optimising). Faculty of forest-, geo- and hydrosciences. Dresden, Germany: Technische Universität Dresden; 2006.

[35] Spinelli R, Schweier J, De Francesco F. Harvesting techniques for non-industrial biomass plantations. Biosystems Engineering 2012;113: 319-324.

[36] Filbakk T, Hoibo OA, Dibdiakova J, Nurmi J. Modelling moisture content and dry matter loss during storage of logging residues for energy. Scandinavian Journal of Forest Research 2011;26(3): 267-277.

[37] Filbakk T, Hoibo O, Nurmi J. Modelling natural drying efficiency in covered and uncovered piles of whole broadleaf trees for energy use. Biomass & Bioenergy 2011;35: 454-463.

[38] Ehlert D, Pecenka R. Harvesters for short rotation coppice: current status and new solutions. International Journal of Forest Engineering 2013;24: 170-182.

[39] Sambra A, Sørensen CAG, Kristensen EF. Optimized harvest and logistics for biomass supply chain. Proceedings of European Biomass Conference and Exhibition. Valencia, Spain; 2008, pp. 8.

[40] FAO. Field handbook - Poplar harvesting. In: International Poplar Commission working paper IPC/8, editor. Rome: Forest Management Divison, FAO; 2008, pp. 60.

[41] Idler C, Scholz V, Daries W, Egert J. Loss reduced storage of short rotation coppice. Žemės Ūkio Inžinerija, Mokslo Darbai 2005;37: 124-134.

[42] Garstang J, Weekes A, Poulter R, Bartlett D. Identification and characterization of factors affecting losses in the large-scale, non ventilated vulk storage of wood chips and development of best storage practices. DTI/Pub URN 02/1535. London: First Renewables Ltd. for DTI; 2002, pp. 119.

[43] Spinelli R, Nati C, Magagnotti N. Using modified foragers to harvest short-rotation poplar plantations. Biomass & Bioenergy 2009;33: 817-821.

[44] Spinelli R, Magagnotti N, Picchi G, Lombardini C, Nati C. Upsized harvesting technology for coping with the new trends in short-rotation coppice. Applied Engineering in Agriculture 2011;27: 551-557.

[45] Schweier J, Becker G. New Holland forage harvester's productivity in short rotation coppice: evaluation of field studies from a German perspective International Journal of Forest Engineering 2012;23: 82-88.

[46] Ceulemans R. POPFULL. Antwerp (BE). [Updated 2014 September; cited 2014 October 13]. Available from: http://uahost.uantwerpen.be/popfull/?lang=en. 2010.

[47] Verlinden MS, Broeckx LS, Ceulemans R. First vs. second rotation of a poplar short rotation coppice: above-ground biomass productivity and shoot dynamics Biomass & Bioenergy, under revision.

[48] Gierkink Machine Techniek BV. Producten - GMT 035. Vragender (NL). [Updated 2014; cited 2014 June 20]. Available from: http://www.gierkinkmt.nl/producten/gmt-035#2-technische-gegevens. Kapelweg 44 - 7134 RJ Vragender, The Netherlands; 2014.

[49] Spinelli R, Laina-Relano R, Magagnotti N, Tolosana E. Determining observer and method effects on the accuracy of elemental time studies in forest operations. Baltic Forestry 2013;19: 301-306.

[50] ESRI. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute. 2011.

[51] New Nordic Biomass a/s. Personal communication. 2014.

[52] Belgian Federal Government. Officieel tarief van de aardolieproducten in euro (Official petroleum rate in euro). http://economiefgovbe/nl/statistieken/cijfers/energie/prijzen/#UxWbfPl5OkE (in Dutch). 04/03/2014 ed; 2013.
[53] R core team. R: A language and environment for statistical computing. R foundation for statistical computing. Vienna, Austria; 2013.
[54] Monti A, Fazio S, Venturi G. The discrepancy between plot and field yields: Harvest and storage losses of switchgrass. Biomass & Bioenergy 2009;33: 841-847.
[55] Berhongaray G, El Kasmioui O, Ceulemans R. Comparative analysis of harvesting machines on an operational high-density short rotation woody crop (SRWC) culture: One-process versus two-process harvest operation. Biomass & Bioenergy 2013;58:333-342.
[56] Hauk S, Wittkopf S, Knobe T. Analysis of commercial short rotation coppices in Bavaria, southern Germany. Biomass & Bioenergy 2014;67:401-412.

Table 1

	Performance (ha h^{-1})	stdev	Productivity (t h^{-1})	stdev	Cost per hour (€ h^{-1})	stdev	Cost per hectare (€ ha^{-1})	stdev	Cost per tonne (€ t^{-1})	stdev
Manual harvesting	0.05	0.03	1.23	0.60	29	12	715	941	44	50
Mechanised harvesting	1.97	0.53	9.50	1.47	330	0	652	176	19	4
Hauling	0.14	0.09	5.34	2.98	68	11	722	625	33	31
Chipping	0.31	0.09	8.19	3.06	242	87	1787	2913	26	8
Cut-and-store – manual	0.50		14.76		338		3224		104	
Cut-and-store – mechanised	2.42		23.03		640		3162		78	
Cut-and-chip	2.52	2.28	14.91	6.79	223	100	524	197	17	6

Table 2

Harvester type	Stemster MKIII	GMT035
Tractor type	John Deere 6920	John Deere 1110E
Manufacturer harvester	Nordic Biomass, DK	Gierkink Machine Techniek BV, NL
Weight harvester (ton)	7	0.150
Weight tractor (ton)	6	17.3
Maximum harvestable diameter (cm)	15	35
Optimal cutting height (cm)	10 - 20	Not specified
Biomass storage capacity (ton)	4.5	12

Table 3

	Performance (ha h^{-1})	Productivity (t h^{-1})	Cost per hour (€ h^{-1})	Cost per hectare (€ ha^{-1})	Cost per tonne (€ t^{-1})
Manual harvesting	0.01	0.15	55	8688	365
Mechanised harvesting	0.37	8.84	289	779	33
Hauling	0.18	4.24	155	870	37
Chipping	0.39	9.37	230	584	25
Cut-and-store – manual	0.58	13.76	440	10142	426
Cut-and-store – mechanised	0.94	22.45	674	2232	94

Figure 1

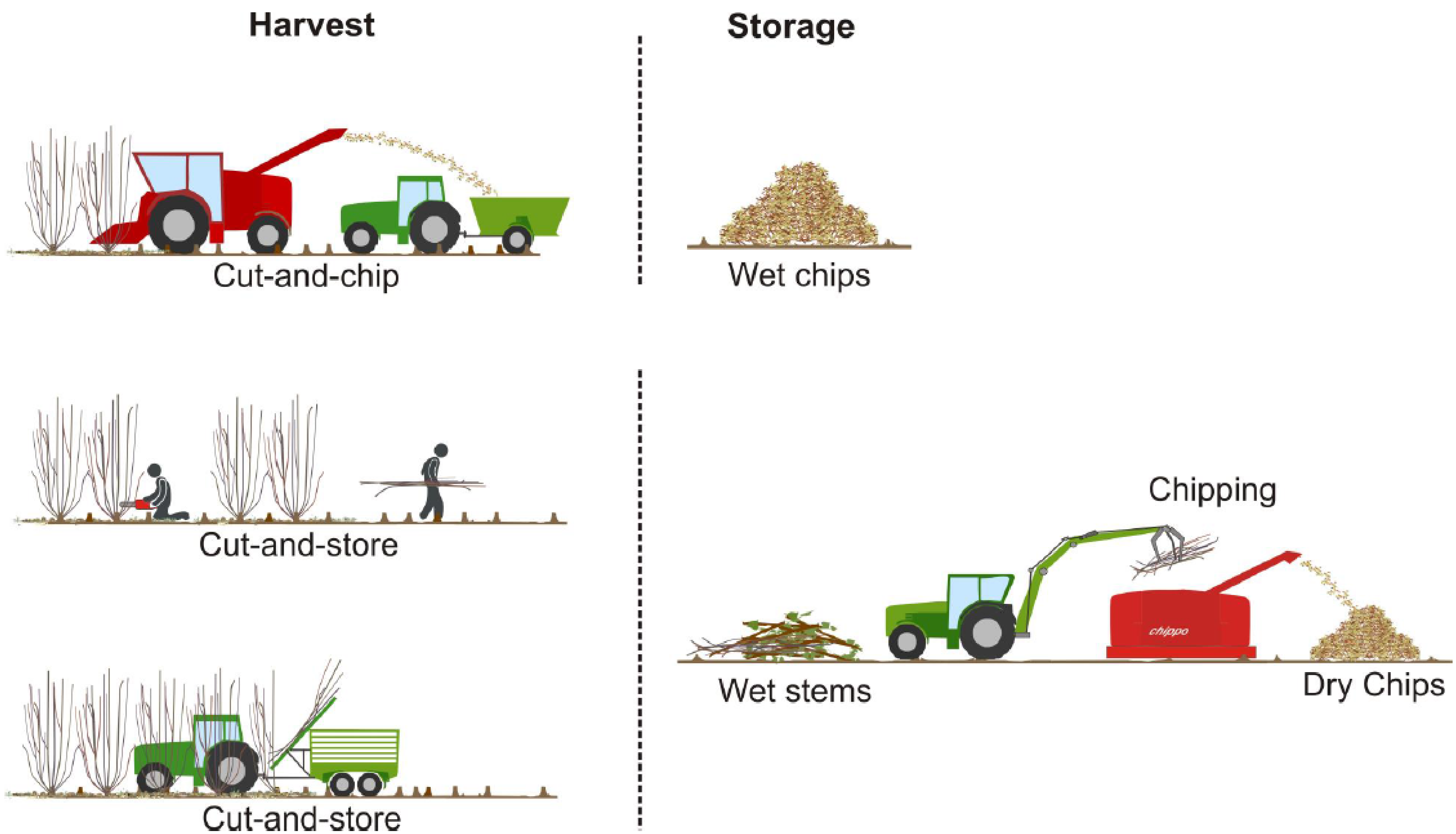
Harvest
Storage
Cut-and-chip
Wet chips
Cut-and-store
Chipping
Wet stems
Dry Chips
Cut-and-store

Figure 2

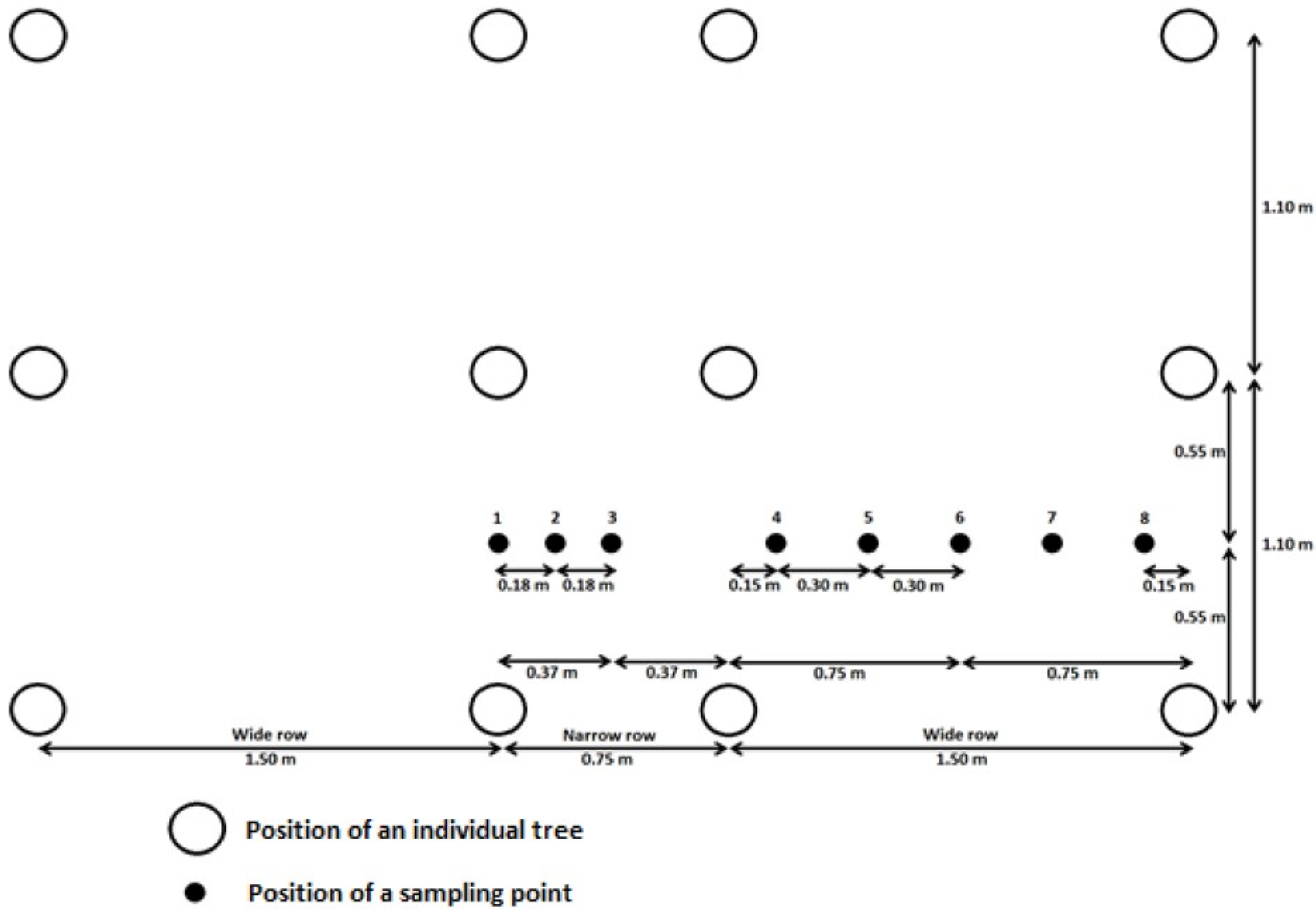
1.10 m
0.55 m
1.10 m
0.55 m
1
2
3
4
5
6
7
8
0.18 m
0.18 m
0.15 m
0.30 m
0.30 m
0.15 m
0.37 m
0.37 m
0.75 m
0.75 m
Wide row
1.50 m
Narrow row
0.75 m
Wide row
1.50 m
Position of an individual tree
Position of a sampling point

Figure 3

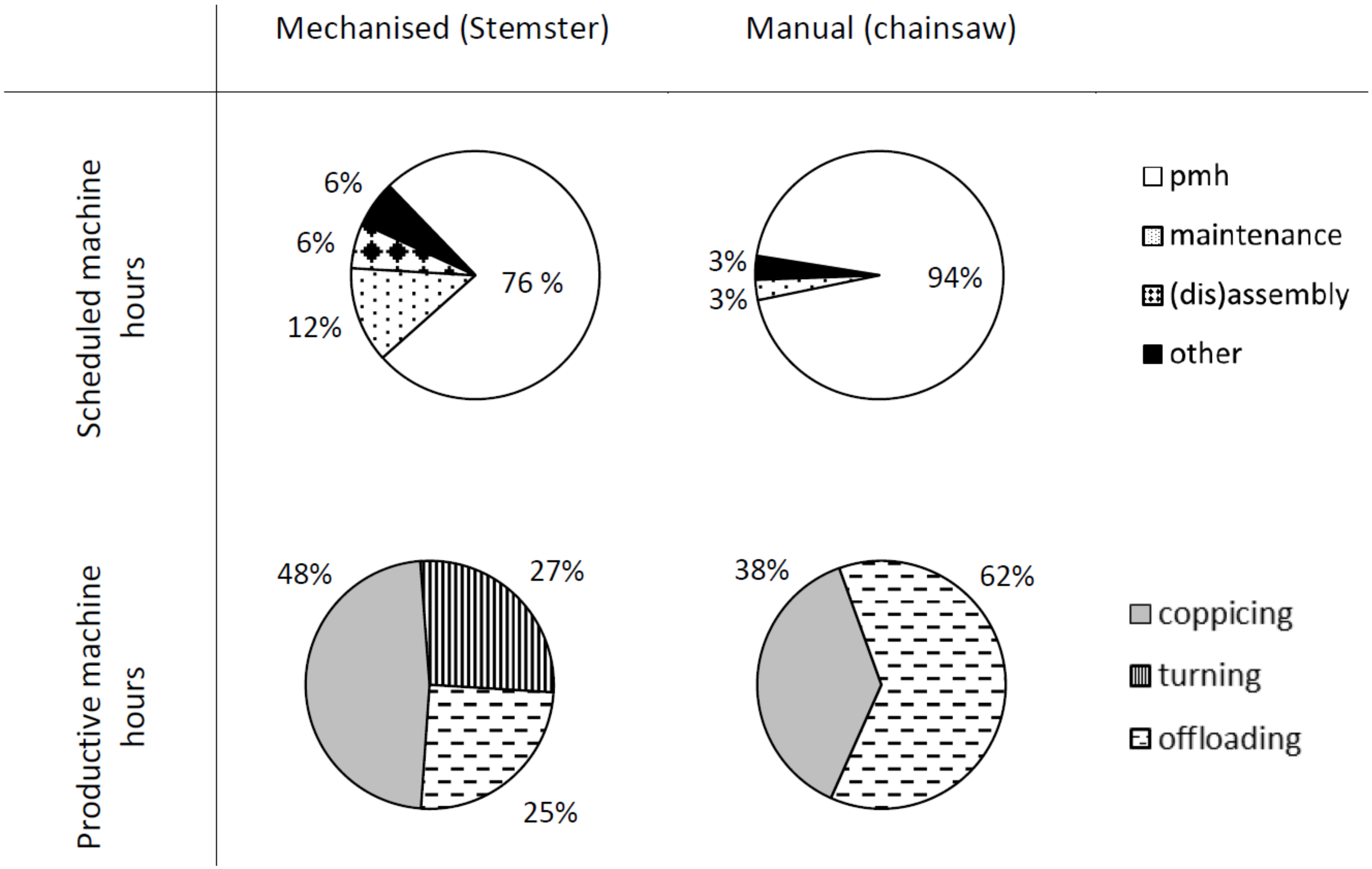
Mechanised (Stemster)
Manual (chainsaw)
Scheduled machine hours
Productive machine hours
6%
6%
12%
76 %
3%
3%
94%
pmh
maintenance
(dis)assembly
other
48%
27%
25%
38%
62%
coppicing
turning
offloading

Figure 4

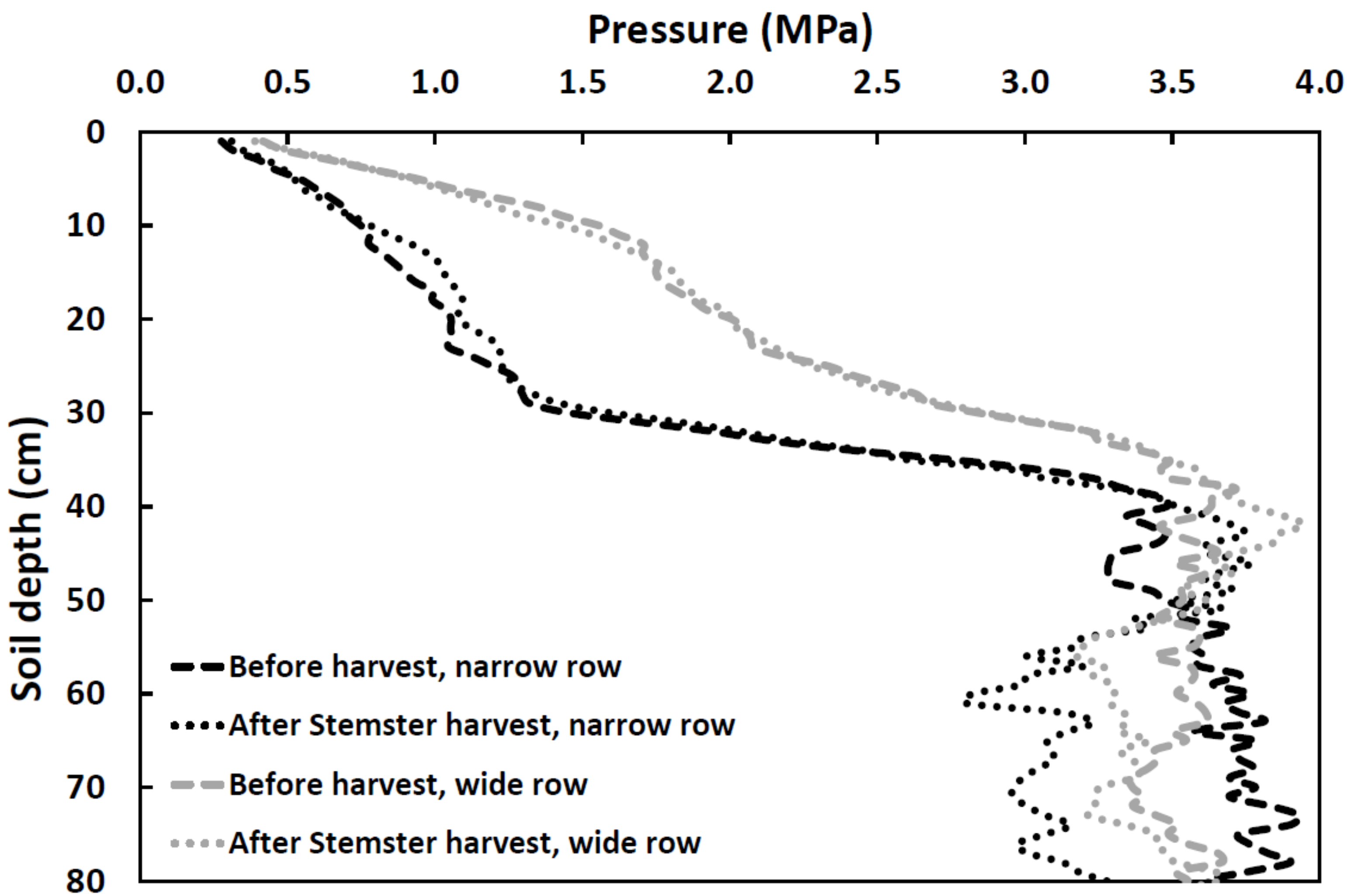
Pressure (MPa)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Soil depth (cm)
0
10
20
30
40
50
60
70
80
Before harvest, narrow row
After Stemster harvest, narrow row
Before harvest, wide row
After Stemster harvest, wide row

Figure 5