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Harvest technology for short rotation coppices and costs of harvest, transport and storage

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Abstract. The lack of knowledge regarding cost-efficient design of whole production chains as well as the availability of powerful harvest machinery are some of the main obstacles for competitive production of bioenergy from short rotation coppices (SRC) at practice. In general, two different harvest lines are available: the cut-and-chip and the cut-and-store lines. Whereas the cut-and chip line provides wood chips which have to be stored until next heating season, the product for intermediate storage of the cut-and-store line are whole trees. Both process lines have major differences not only in harvesting, but also in transport, storage and process losses leading to different costs of the end product wood chips. On basis of data from several SRC harvest campaigns, production costs for wood chips have been calculated to identify best practice solutions taking the following factors into account: chip size determined by the harvest system, storage including related costs and losses, field size and shape as well as transport to storage. According to the results, mower-chippers and forage harvesters can provide wood chips at lowest production costs (43…45 € t_{dm}^{-1}) if field shape is favourable for harvest operations. Under less favourable field conditions costs are approx. 7 to 14% higher. Highest production costs have to be accepted if whole trees are harvested with a shoot harvester (64 to 72 € t_{dm}^{-1}). The reduction in storage losses and storage costs are not sufficient to compensate higher machine costs for harvest and additional comminution with mobile chippers from forestry.

Key words: short rotation coppice, poplar, willow, harvest, costs.

INTRODUCTION

Cropping short rotation coppices (SRC) on agricultural land is a promising option for environmentally friendly production of biomass and concurrent improvement of farmer's income. Under European climate conditions fast growing trees such as poplar (*Populus sp.*), willow (*Salix viminalis*), and black locust (*Robinia pseudoacacia L.*) cultivated in SRC plantations or agroforestry systems have the potential for production of more than 10 t_{dm} $ha^{-1}yr^{-1}$ woody biomass (Scholz et al., 2011; Benetka et al., 2014; Larsen et al., 2014). Usually, the produced wood is harvested as wood chips for the production of heat in local boilers at farms or in regional heating plants. At present, approx. 50,000 ha of short rotation coppices are farmed in Europe (Pecenka et al., 2014a) respectively more than 5,000 ha in Germany (Murach et al., 2013; Wirkner, 2015). However, for the transition of cropping SRC from demonstration to agricultural practice, several problems have to be solved. Different investigations of the current situation in the management of SRC have shown that harvest costs alone represent 35 to 60% of the total costs of biomass production from SRC (Schweier & Becker, 2012a; Ehlert &

Pecenka, 2013). Several machine developments have been carried out with the target to reduce harvest costs in the last 30 year, but only few systems reached marketability (Hartsough & Spinelli 2001, Baldini & Fulvio 2009, Abrahamson et al. 2010; Berhongaray & Kasmioui 2013; Eisenbies et al. 2014).

MATERIALS AND METHODS

Analysis of harvest equipment and process lines

Harvest lines for SRC can be classified according to the level of mechanisation, the combination of process steps, the produced assortments of wood, or the rotation length (Scholz et al., 2008). With focus on the combination of process steps necessary for harvest the most successful harvest machine developments can be grouped in two different harvest lines: *1) Cut-and-Chip lines* and *2) Cut-and-Storage lines*.

Cut-and-Chip harvesting is a one-step operation converting standing biomass into wood chips using modified forage harvesters or tractor mounted respectively tractor pulled chippers. Freshly harvested wood chips have moisture contents of 50 to 60%. Therefore, wood chips have to be dried in dependence to following storage operations and later use to reduce mass losses and mould contamination (Garstang et al., 2002). Two different systems are currently used in practice for cut-and-chips lines (Fig. 1):

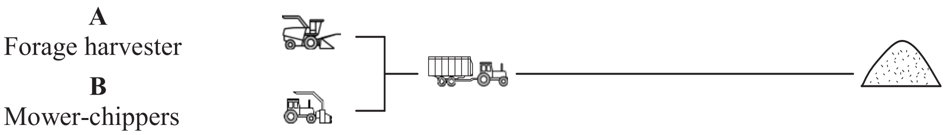

Figure 1. Cut-and-chip harvest of wood chips from SRC.

A) Forage harvesters: For harvesting SRC with self-propelled forage harvesters, these machines have to be equipped with special cutter-headers designed for cutting the trees from the stools, pushing them down to an almost horizontal position, and continuous feeding of these trees to the chipping drum of the harvester. Such machines proved to work very efficient for poplar and willow planted in single or double rows (Fig. 2). Problems have been reported from older plantations (> 3 year), bigger trees (diameter at cutting height of more than 15 cm), from very dense plantations or older plantations with naturally wider stools. The harvested material consists of wood chips with particle length between 16 to 45 mm, classified as P31S according to standard DIN EN ISO 17225-4. Several investigations regarding productivity of self-propelled forage harvesters at SRC harvest have been carried out in the last 10 years (Spinelli et al, 2009; Burger, 2010; Schweier & Becker, 2012a; Pari et al., 2013). However, it's very difficult to compare these results among each other due to the fact, that there are manifold factors influencing the productivity such as field design, age of trees and stools, rotation cycle, tree variety, location and weather conditions. In average, a productivity of 15 to 21 t_{dm} per scheduled machine hour can be expected under typical harvest conditions.

B) Mower-chippers are tractor-mounted or tractor-pulled harvest devices designed for cutting and chipping trees in a single operation comparable to harvest with forage harvesters. Several developments have been started in the last 20 year (Ehlert et al., 2013) but only very few machines have reached marketability until now. Such machines can be mounted at front- or backside of standard tractors (e.g. JENZ GMHT 140). Newer developments (e.g. ATB mower-chipper – Fig. 3 – or 'Göttinger' auger-chipper) are design for chipping trees in an upright position. Harvesting trees without pushing trees down before chipping has several major advantages: Older and very dense plantations can be harvested, damaging stools during harvest can be avoided, and in dependence to the design of the mower-chipper also trees with diameters at cutting height of 15 cm and more can be harvested. These harvesters are typically designed to produce coarse wood chips to take advantage of favourable storage and drying behaviour of bigger chips (Pecenka et al., 2014b). The harvested material consists of wood chips with length between 20–100 mm, classified as P45S according to standard DIN EN ISO 17225-4. According to investigations of Burger (2010) and Ehlert &Pecenka (2013) a productivity of 10 to 12 t_{dm} per scheduled machine hour can be expected under typical harvest conditions.

Figure 2. Modified forage harvester.

Figure 3. ATB mower-chipper.

Table 1 shows the results of different field studies in detail which have been analysed regarding costs and productivity of cut-and-chips harvest equipment used at practice.

Table 1. Productivity and costs of different machines for cut-and-chip harvest at practice (Pecenka & Schweier 2014)

A Forage harvester			
Harvest system (model/header)	Productivity (t_{dm} smh^{-1}) *	Costs (€ t_{dm}^{-1})	Reference
New Holland/FB130	10.2–21.7	12.94–27.55	Schweier & Becker 2012a
New Holland/FB130	4.2–13.2	25.19–47.30	Kern 2012
Claas/GB1	Ø 16.1	Ø 14.60	Spinelli et al. 2009
Claas/HS2	Ø 7.7	Ø 26.40	Spinelli et al. 2009
Krone/HTM	11.1–23.3	11.60–24.20	Spinelli et al. 2011
B Mower-chippers			
Auger chipper ('Göttinger')	3.4	12.27	Burger 2010
ATB Mower chipper	6.6–9.9	15.30–21.50	Pecenka & Schweier 2014

* t_{dm} … ton dry matter, smh … scheduled machine hour

Cut-and-Storage harvesting are two-step process lines which are usually known from forestry with special advantages at harvest of older trees. Commonly they are applied for trees of bigger diameter when harvest with agricultural equipment is not possible or storage of whole trees is considered as advantageous (Fig. 4).

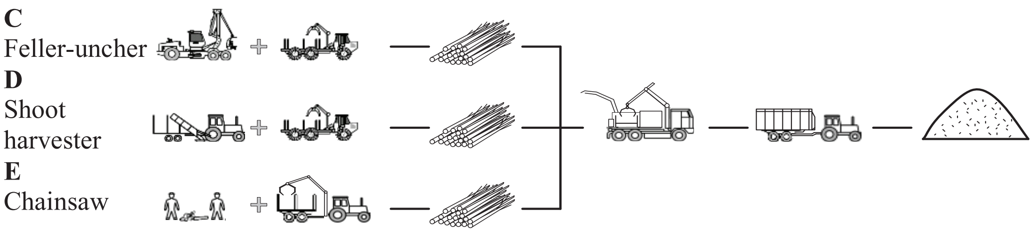

Figure 4. Cut-and-storage harvest of wood chips from SRC.

Whereas cut-and-chip lines are characterised by simultaneous mowing and comminution of the trees, cut-and-storage lines are two step harvesting with intermediate storage of trees in big piles at field site. Generally, due to the more complex process and the higher number of involved machines during harvest cut-and-storage lines have a lower productivity than cut-and-chip lines.

C) Feller-buncher / Harvest with forest equipment: Feller-bunchers (Fig. 5) are standard harvest equipment from forestry designed for harvesting smaller trees such as small or energy wood. Feller-buncher headers (e.g. Timberjack TJ 720) can be mounted on forestry harvesters to cut, collect and pile bundles of trees between the rows. Later on, a forwarder can be used to collect the tree bundles, transport them to storage place and pile them for drying by natural aeration. According to time studies from the last years (Burger, 2010; Spinelli et al., 2011) the productivity averages from 4 to 14 t_{dm} per scheduled machine hour (∅ 8.6 t_{dm}).

D) Shoot harvester are special machinery design for harvesting and collecting whole shoots (trees) from SRC (e.g. Stemster MKIII, Fig. 6). The trees are continuously cut and collected on the loading floor of the machine. If a forwarder is used for transport of trees to the storage place, the productivity of harvest can be increased. Trees with diameters of 15 to 20 cm at cutting height can be harvested. According to Schweier & Becker (2012b) a productivity of 16 to 21 t_{dm} per scheduled machine hour can be expected.

E) Manual harvest with a chainsaw: At very small fields, regional scattered fields or on very wet fields with difficult soil condition harvesting with heavy machines is not productive or often not possible. In such cases manual harvest with a chain saw is an option (Fig. 7). To increase working progress, harvest should be organised in teams of two workers – one cutting and the other pre-piling the trees for later faster collection by a forwarder. However, according to Burger (2010), Schweier & Becker (2012c) and Schneider (1995) the productivity is very low with an average of 3.6 t_{dm} per scheduled machine hour.

Table 2 shows the results of different field studies in detail which have been analysed regarding costs and productivity of cut-and-storage harvest equipment used at practice.

Table 2. Productivity and costs of different machines for cut-and-storage harvest at practice (Pecenka & Schweier 2014)

Harvest system (model)	Productivity (t_{dm} smh^{-1}) *	Costs (€ t_{dm}^{-1})**	Reference
C Feller-buncher (forest harvester)			
Valmet 921	7.7–9.6	11.50–14.30	Spinelli et al. 2011
Timberjack 1270A	Ø 5.8	Ø 12.90	Burger 2010
Hitachi EX 165	Ø 16.2	Ø 3.60	Schweier et al. 2014
D Shoot harvester			
Stemster MK III	8.1–11.3	29.23–40.78	Schweier & Becker 2012b
E Chain saw			
Stihl 026	1.6–2.3	31.80–45.50	Burger 2010
Stihl 026	0.9–1.7	43.40–81.90	Schweier & Becker 2012c
Chain saw & brush saw	0.4–0.7	105.30–184.30	Schneider 1995

* t_{dm} … ton dry matter, smh … scheduled machine hour;
** labour costs at harvest with chain saw/brush cutter 35 € h^{-1}, machine costs (chain saw) 3.73 € smh^{-1}.

Figure 5. Feller buncher.

Figure 6. Shoot harvester.

Figure 7. Manual harvest.

After storage and drying in the storage pile, the trees have to be comminuted to wood chips before transport to end user for all cut-and-storage lines. Standard mobile chipper-trucks or tractor-driven chippers from forestry can be used for this operation. According to Nahm et al. (2012), Kuptz & Hartman (2014) and Schweier et al. (2013) productivities of 40 to 110 m³ of wood chips can be reached at chipping of poplar from SRC at average costs of approx. 4 € m^{-3}.

Analysis of harvest costs

Practice experience and many time studies from different European countries have shown that powerful machinery for harvest of SRC is available. Test resp. practice conditions have been always very different at the majority of these time studies. Thus, it's difficult to compare harvest systems regarding final costs for the production of wood chips from SRC. Therefore, a cost calculation model has been developed, taking typical costs, performance data as well as different field layouts into account. For modelling typical field layouts a field model is required.

Field model: Three different typical field shapes have been used for calculation of production costs. The total size of the considered field has been kept constant (3 ha). As shown in Table 3, with increasing field length the number of necessary turnings at the end of the rows declines and the percentage of field area covered with trees (effective planting area) increases.

Table 3. Models of different 3 ha fields used for the calculation of harvest costs

	Field 1	Field 2	Field 3
Field size and shape (width x length)	3 ha (300 x 100 m)	3 ha (200 x 150 m)	3 ha (100 x 300 m)
Required headland for turning	2 x 10 m (6,000 m²)	2 x 10 m (4,000 m²)	2 x 10 m (2,000 m²)
Effective planting area	2.4 ha (80%)	2.6 ha (87%)	2.8 ha (93%)
Row length	80 m	180 m	280 m
Row distance	2.4 m	2.4 m	2.4 m
Number of rows (total)	125	63	42

Harvest performance and productivity: On the basis of own experiments and results from work times studies from literature (see Table 1 & 2) basic data for performance, productivity and costs of different harvest solutions have been compiled for calculation of production costs of wood chips from SRC. Storage and transport costs as well as losses during harvest, 6-months storage, chipping of whole trees after storage (as required for cut-and-storage lines C – E) and handling have been incorporated into the cost model (Table 4 and 5).

Table 4. Basic data for calculation of harvest costs in cut-and-chip lines

Harvest line Cut-and-chip	**A** Forage harvester (e.g. New Holland/FB130)	**B** Mower-chipper (e.g. ATB mower-chipper)
Performance ($ha\ h^{-1}$) *	0.74	0.42
Productivity[1)] ($t_{dm}\ h^{-1}$)	21	12
Turning time (s per row)	50	50
Machine costs (€ h^{-1})	300	150
Specific transport costs (€ t_{dm}^{-1})		
distance 5 km	10.67	10.67
10 km	15.29	15.29
Mass losses during harvest, storage and transport (%)	20	20
Planting	Poplar in single row (8,000…10,000 plants per ha) stem diameter at cutting height 6…12 cm	
Rotation cycle (years)	3	3
Annual dry matter yield/biomass growth ($t_{dm}\ ha^{-1}\ yr^{-1}$)	10	10

* At optimum field shape conditions of field 3

Table 5. Basic data for calculation of harvest costs in cut-and-storage lines

Harvest line Cut-and-storage	**C** Feller-buncher (e.g. Hitachi EX 165)	**E** Chainsa w	**D** Shoot harvester (e.g. Stemster MKIII)
Performance (ha h^{-1}) *	0.12	0.05	0.75
Productivity[1)] (t_{dm} h^{-1})	8.6	3.6	21
Turning time (s per row)	0	0	45
Machine costs (€ h^{-1})			
Harvest machine (€ h^{-1})	95	34	300
Forwarder (€ m^{-3})	3.2	3.2	2.9…3.8
Chipper (€ m^{-3})	4	4	4
Specific transport costs (€ t_{dm}^{-1})			
distance 5 km	8.90	8.90	8.90
10 km	11.80	11.80	11.80
Mass losses during harvest, storage and transport (%)	15	15	15
Planting	Poplar in single row (4,000…5,000 plants per ha) stem diameter at cutting height 15…20 cm		Poplar in single row (8,000…10,000 plants per ha) stem diameter at cutting height 6…12 cm
Rotation cycle (years)	8	8	3
Annual dry matter yield/biomass growth (t_{dm} ha^{-1} yr^{-1})	10	10	10

* At optimum field shape conditions of field 3

RESULTS AND DISCUSSION

Results of the cost calculations including required transport of wood chips to a storage site in 5 km distance to field are shown in Table 6. For cut-and-storage lines, costs of chipping trees with a mobile chipper after storage and following transport to a storage place on farm (5 km distance) have been calculated too. Due to the fact, that wood chips from cut-and-storage lines are often transported directly to the end consumer after chipping, cost for this option are also given in Table 6.

Comparing all harvest lines, harvest of a field with optimised field shape (field 3) with a mower-chipper (line B) is connected to the lowest harvest costs (approx. 43 € t_{dm}^{-1}) at all, closely followed by harvest with a forage harvester (line A, approx. 45 € t_{dm}^{-1}). Focusing on the influence of the field shape, harvest costs under unfavourable conditions (field 1) are approx. 7% higher for the forage harvester resp. 14% for the mower-chipper.

Due to the high cost of chipping with a mobile chipper, all cut-and-storage lines (D – E) are connected to higher production costs than cut-and-storage lines (A, B). Regarding cut-and-storage, lowest costs of approx. 59 € t dm^{-1} can be realised at manual harvest with a chainsaw (line E, including transport). If the chips can be sold directly from field after chipping, these costs can be reduced to approx. 50 € t_{dm}^{-1}. Further advantages of cut-and-storage lines C and E can be seen in lower costs for cultivation due to a lower planting density and higher chip quality due to higher stem diameters at harvest as a consequence of longer rotation cycles (8 years instead of 3 years in these scenarios – see Table 4 and 5). However, the lower planting density can reduce wood chip costs by 5 € t_{dm}^{-1} at best. If longer rotation cycles essentially improve chip quality as well as consumers are willing to pay a higher price for such chips is doubted at present. Finally, harvest with a shoot harvester (line D) is even less economic than harvest with forestry equipment due to higher machine costs and the high influence of the field layout. Harvest costs of approx. 55 € t_{dm}^{-1} have been calculated if no additional transport from field to storage is required. Due to technical limitations of available shoot harvesters a rotation cycle of 3 year has been assumed for this line. Thus, no advantages of a lower planting density or longer rotations cycles can be credited for line D.

Table 6. Production costs of wood chips from SRC

Harvest line		**Harvest costs**					
		€ t_{dm}^{-1}			€ t^{-1} (x = 30%) [2)]		
		field 1	field 2	field 3	field 1	field 2	field 3
A Forage harvester[1)]		48.1	45.1	45.1	33.6	31.6	31.6
B Mower-chipper[1)]		48.6	44.1	42.8	34.0	30.9	30.0
D Shoot harvester (Stemster)	without transport	63.5	57	55.0	44.4	39.9	38.5
	with transport[1)]	72.3	65.8	63.9	50.6	46.1	44.7
C Feller-buncher	without transport	52.4			39.9		
	with transport[1)]	61.2			46.1		
E Chainsaw	without transport	50.5			35.3		
	with transport[1)]	59.3			41.5		

All costs without travel cost for harvest equipment to field
[1)] Transport distance 5 km
[2)] x = moisture content of fresh matter

For all harvest lines no travel costs for harvest equipment have been calculated due to the fact, that service companies charge farmers very differently in dependence to travel distance from company to field. For instance, prices for distances between 100 to 200 km of 600 to 1,200 € had to be paid in Germany in the last years. If lower planting densities are chosen with the aim of using a cut-and-storage line someone should bear in mind that higher travel costs for the first harvest after 8 years alone are in the same range as possible cost reductions credited for 20 years due to optimised planting. This problem would be even more serious for cut-and-storage lines if more machinery (harvester, forwarder and mobile chipper) is required. Such disadvantages could be only partly compensated by reduced storage losses or transport operations.

In dependence to the field conditions, weather during harvest or availability of harvest equipment real harvest costs and machine performance can vary a lot. Therefore, the influence of variations of main costs factors have been taken into consideration as well. Fig. 8 shows the influence of variations of productivity and harvest machine cost for harvest with a mower-chipper. Harvest machine costs of 150 € h^{-1} and a productivity of 0.42 ha h^{-1} have been used as basic scenario (100%). If productivity is reduced by 30%, the production costs will increase from 43 to 55 € t_{dm}^{-1}. Whereas an increase of machine costs by 30% induces an increase of production costs to 47 € t_{dm}^{-1} only.

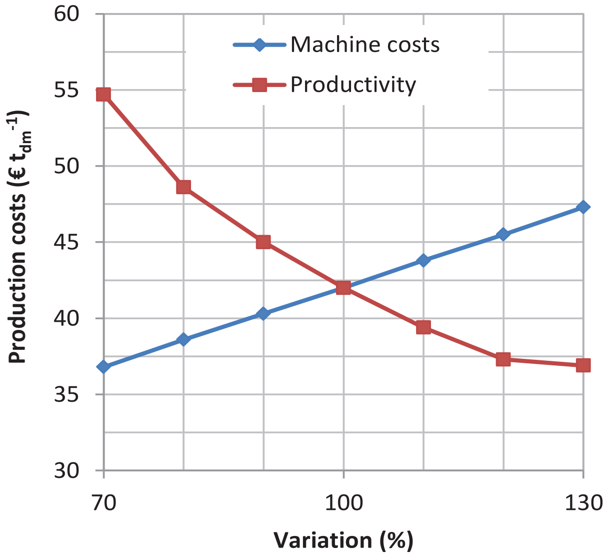

Figure 8. Influence of variations of productivity and machine costs on productions cost for harvest with mower-chippers.

CONCLUSIONS

In general, the availability of harvest equipment at farm or at least in the region where SRC's are cultivated is very important for the reduction of harvest costs. Marked prices for wood chips are a subject to high variations in dependence to the regional structure of supply from forestry and demand from heating plants or other end users. On the basis of a market price of 60 € t_{dm}^{-1} farmers can supply wood chips with profit using all harvest lines investigated in this study. However, for the calculation of sales prices for wood chips from SRC additional costs such as planting cost, rent or costs for reconversion of the plantation to conventional agricultural land (when the stools have lost its productivity) have to be taken into consideration too. According to this study, one step cut-and-chip lines are advantageous because of 20 to 40% lower costs in average compared to cut-and-storage lines. Comparing favourable cut-and-chip lines only, harvest with forage harvesters and mower-chippers are in the same cost range. But cut-and-chip lines on the basis of mower-chippers could be favourable due to lower machine investment costs connected to an improved regional availability of such inexpensive harvest equipment in future. Furthermore, travel costs for harvest with mower-chippers are much smaller because only a car trailer is required for transport and the harvest machine can be operated with standard tractors (130 to 180 KW) available on the majority of all farms. Advantages of cut-an-storage lines can be seen particularly in longer rotation cycles and reduced costs if small fields (< 2 ha) or fields with unfavourable field shapes should be used for SRC. Among these lines, manual harvest with a chain saw showed to be best closely followed by harvest with a feller-buncher.

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