www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

# Harvesting of Short Rotation Coppice – Harvesting Trials with a Cut and Storage System in Germany

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**Schweier, J. & Becker, G.** 2012. Harvesting of short rotation coppice – harvesting trials with a cut and storage system in Germany. Silva Fennica 46(2): 287–299.

Short rotation coppice (SRC) harvesting techniques are available in Germany, but broad experience and knowledge about machine performance and the related effective costs of harvesting operations are still missing. This information is crucial, as harvesting costs strongly influence the economic performance of the overall supply chain. Therefore, it was the aim of this study to collect and analyze productivity data of different harvesting systems for SRC. The combined cut and chip system on the one hand and the cut and storage system on the other hand were studied by literature review. Several studies analyze the combined cut and chip systems and the reported machine productivities showed great variations. The average was 30 green tons per scheduled machine hour (gt smh$^{-1}$). Few studies are analysing the cut and storage system. They report that machines still are under development and that further research is needed. Therefore, time studies of harvesting operations using the cut and storage system were carried out. Five trials were performed with the harvesting machine "Stemster MK III" developed by Nordic Biomass. The share of productive working time was 85% and the average productivity was 21 gt smh$^{-1}$. These results were compared with values from the literature. Resulting harvesting costs were calculated per oven dry ton (€ odt$^{-1}$). The advantages and disadvantages of both harvesting systems are highlighted.

**Keywords** harvest operations, marginal sites, productivity, SRC, Stemster MK III
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**Received** 20 September 2011 **Revised** 6 March 2012 **Accepted** 6 March 2012
**Available at** http://www.metla.fi/silvafennica/full/sf46/sf462287.pdf

# 1 Introduction and Problem

Biomass as raw material for European energy production has received raising interest during the last decades from policy makers, energy utilities, farmers and investors (Djomo et al. 2011). This is also in reaction to the European Commission who established the binding target of a 20% overall share of renewable energy sources in the EU's energy consumption by 2020 (COM 2008). Among the various crops for biomass options, especially short rotation coppice (SRC) is regarded as a strategic resource of wood products (FAO 2008) as both, poplars and willows are fast-growing and high-yielding species which can be managed and regenerated as a coppice system (Djomo et al. 2011, Al Alfas et al. 2008). Intensive breeding programs resulted in a number of clones with high production rates for a wide range of climates and sites within the EU (Liberloo et al. 2006, Deckmyn et al. 2004). Additionally, SRC is a very extensive form of land management in comparison to conventional agriculture, as crops are harvested in a 2–5 year cycle (DEFRA 2004). The conversion paths of biomass from SRC are manifold: biomass can be used for burning to generate power and/ or heat in combustion plants, it can be used for gasification where biomass is used in gas combined cycle plants and in biomass to liquids (BtL) plants to produce biofuels for the transportation sector (Börjesson and Ahlgren 2010).

While SRC reached production scale in many European countries, it is still at a marginal level in Germany. The process of establishment of SRC just started during the last 2–3 years and up to now, in 2010/ 2011 about 3000–4000 ha SRC are cultivated (FNR 2010), mostly poplar growing in the first rotation. There are several reasons which restrict faster developments, e.g. high prices for agricultural crops like wheat and corn in the last years in comparison to the relatively low market price for energy wood chips from SRC due to e.g. missing market opportunities or too little experience of cultivation and harvesting. There are also technological questions to solve: some harvesting techniques are available, but broad experience and knowledge about machine performance and effective costs of harvesting operations is often missing. This information is crucial, as harvesting costs strongly influence the economical performance of the overall supply chain (Djomo et al. 2011).

SRC are usually harvested in winter after leaf fall and before leaf set, preferably when soils are frozen (Forestry Commission 1998). Technically, there are two different systems to harvest SRC, the cut and storage system and the more common combined cut and chip system. With the last-mentioned, SRC are harvested with an agricultural forage harvester (e.g. for maize and sugarcane), either self propelled or tractor mounted, whose standard header is replaced by a special cutting head. Chips are blown into an accompanying tractor-pulled trailer which transports the chips to an interim or final storage (Sambra et al. 2008, FAO 2008). With the cut and storage system, trees are usually cut and collected in one step. They are moved to a storage area and are chipped after storage.

The aim of this study is to perform time studies of harvests of SRC using cut and storage system and to evaluate and compare the results regarding productivities and costs with the more common cut and chip system, based on literature reviews.

# 2 Existing Studies

Spinelli et al. (2008, 2009) analyzed the machine productivity of different Claas Jaguar forage harvesters (840, 850, 860, 880, 900) equipped either with the HS-2 or the GBE-1 cutting head. The average machine productivity was 35 green tons (gt) per scheduled machine hour (smh$^{-1}$) and 25 gt smh$^{-1}$ respectively. The highest productivities were reached when using the most powerful engine in both studies. Kienz (2006) and Heinrich (2006) analyzed harvesting trials with two Claas Jaguar forage harvesters equipped with prototype cutting heads developed by Henriksson and Petterson. The technical machine productivity ranged from 16–42 gt per productive machine hours (pmh). Delays accounted for 33–52% of the total working time (twt) mostly because of deficits in logistic planning, which resulted in long waiting times as well as because of machine breakdowns due to e.g. inhomogeneous diameters causing frequent blocking of saw blades. Only few studies were identified which analyze other combined cut and chip machines than the Claas Jaguar (Becker et al. 2010, Burger 2010, Schweier and Becker 2012). Schweier and Becker (2012) studied the heavy New Holland forage harvester FR 9060 equipped with the cutting head FB 130. The average share of productive working time was 71%, it took 1.34 $pmh^{-1}$ to harvest one hectare and the average machine productivity was 31 gt $smh^{-1}$.

To summarize the information identified in literature, approximately 30 green tons are harvested per scheduled machine hour and the average productive working time is 70% when using forage harvesters. Well organized chip logistic is required. When excluding turns and delays in logistics productivities up to 80 green tons per productive machine hour can be reached (Scholz et al. 2008, Spinelli et al. 2009).

However, biomass harvested with combined cut and chip systems result in high moisture contents (MC) of the chips and further drying may be needed to reach lower MC for efficient thermal conversion into energy. To reach this, chips can be dried and stored under covered chip piles or under roofs (Basari and Manzone 2010, Pari et al. 2008). This way of handling is costly and may cause emission problems and dry matter losses due to extreme increase in temperature, depending on duration and conditions of storage (Idler et al. 2005, Garstang et al. 2002).

To avoid these problems, the cut and storage system may be an interesting alternative. Whole trees are cut and bundled or cut and accumulated, then loaded and transported to the end of a row or a defined place at the field and stored for drying (Gigler et al. 2000, Filbakk et al. 2011, Eriksson and Gustavsson 2010). When trees are dried to MC of 20–25% they are chipped and biomass chips are delivered to the plant (Kaltschmitt et al. 2009). Under the conditions of fragmented SRC-parcels, biomass can be collected from several fields and chipped efficiently just in time before delivery. As a result, upgraded chips with higher revenues can be expected and no additional investment, space or time for drying or storage is needed.

Today, few harvesting machines applying this concept exist and most of them are prototypes. Scholz et al. (2009), Danfors (1992), Hartsough and Spinelli (2001) and Wickham et al. (2010) mention the cut and storage system but strongly argue for further research to "quantify and compare the economics" (Wickham et al. 2010). In 1998, a technical note was published in which results of field trials of harvests in the UK were presented (Forestry Commission 1998). In the study, 4 harvesters following the principle of the cut and storage system have been tested. The productivities of the machines varied between 0.09–0.22 ha $smh^{-1}$. Resulting costs were two times higher than in the cut and chip system. Mitchell et al. (1999) report 0.53 ha $smh^{-1}$ for the Empire 2000 and 0.13 ha $smh^{-1}$ for the Loughry, both machines are following the cut and storage system. Danfors and Nordén (1995) also used the Empire 2000 and reached productivities of 0.75 ha $smh^{-1}$ (17.8 gt $smh^{-1}$) on average. Other trials using the Fröbbesta harvester resulted in lower productivities (0.36 ha $smh^{-1}$; 15.7 gt $smh^{-1}$) (Danfors and Nordén 1995). Pari and Civitarese (2009) conducted trials with a felling-windrowing machine with which stems are cut and put parallel to the advancing direction of the machine and reached working productivities up to 1.2 ha $smh^{-1}$. The authors expect positive effects especially for sites with low bearing capacity soils. Caslin et al. (2010) report of harvesting trials using a harvester following the cut and storage system. Detailed results are not presented but the authors report harvest productivities of 4–6 ha $day^{-1}$.

To summarize, the reported productivities identified in literature are 16.8 gt $smh^{-1}$ and 0.5–1.2 ha $smh^{-1}$ on average (Caslin et al. 2010, Pari and Civitarese 2009, Danfors and Nordén 1995). All authors come to the conclusion that the cut and storage system is still under development but they see great potential for the future due to the named advantages.

# 3 Material and Methods

## 3.1 Description of the Harvesting Machine "Stemster MK III"

According to the manufacturer Nordic Biomass, the Stemster machine (Fig. 1) was constructed for harvesting 3–4 year old willow SRC under Scan-

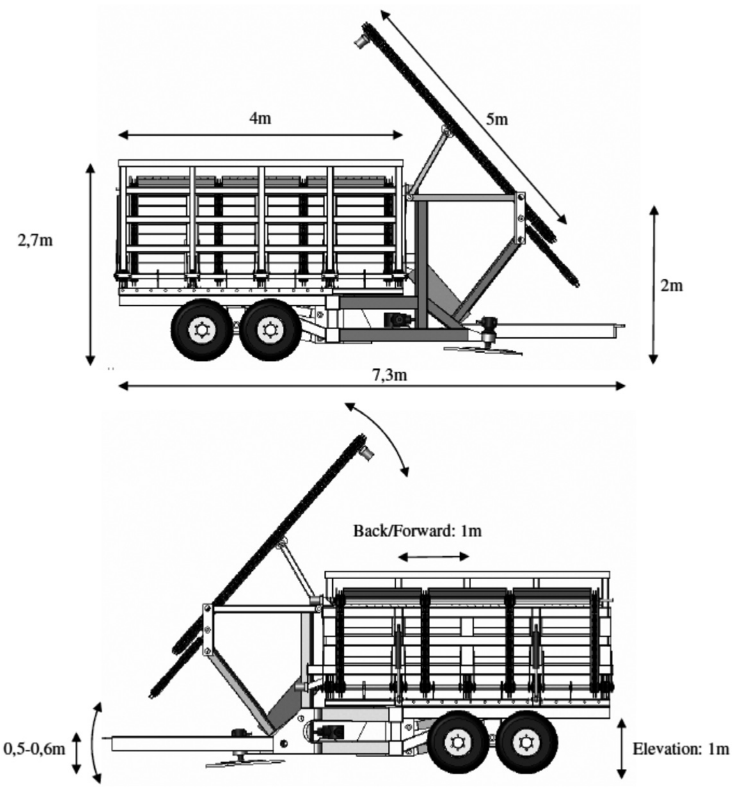


**Fig. 1.** Side view of the harvesting machine Stemster MK III (proximal measurements, in meters) (Source: Nordic Biomass 2008).

dinavian conditions and was used in this study to harvest poplar in Germany for the first time (valid for fields 1 to 4). The technical requirement for the tractor is that it can pull the machine's weight (7 tons) and has an engine minimum of 95 kW to power the Stemster MK III. In the present study, a John Deere tractor 8520 T (243 kW) was used. Both machines weight together approximately 12 tons which is comparable to the weights of forage harvesters, but in this case the Stemster carries the harvested trees and no further accompanying tractor with trailer is needed. The saw blades are fixed at the front of the machine. The height of the saw blades can be adjusted by lowering or raising the whole machine. Adjustment to the side is possible by swinging the tow bar left/ right, which turns the whole machine in relation to the tractor. In this manner the machine can be steered into the rows (Nordic Biomass 2008). Depending on conditions it can be operated with speeds up to 10 km/h. Harvesting is performed by cutting the stems with double saw blades at a height of 10–15 cm above the ground. Just before cutting stems are caught by the elevators conveyor chains, which hold the stems during the cutting, and then transports them to the machines storage space. This looks like a box and has a capacity for 4.5 tons. The storage space consists of a floor with conveyor chains and a fixed side board. Opposite to the fixed side board, the storage space is equipped with a left/ right collapsible side board. This is also equipped with conveyor chains, similar to the storage's floor. The conveyor chains are used during harvesting, to compact the load, by moving the stems side ways within the storage space. Offloading is possible by lowering the collapsible side and letting the conveyor chains move the load over the side. The storage space can slide 1m back- and

**Table 1.** Field data.

| Parameter | Study 1 | Study 2 | Study 3 | Study 4 | Study 5 |
|---|---|---|---|---|---|
| Size of field (ha) | 1 | 1.7 | 4.1 | 7.4 | 1.1 |
| Average length of row (m) | 115 | 298 | 423 | 400 | 192 |
| Plant design | single row | single row | single row | single row | double row |
| Plant density (1000 trees $ha^{-1}$) | 11.1 | 10 | 10 | 11.1 | 14.8 |
| Diameter, at breast height (cm) | 3.0 | 2.8 | 3.1 | 2.7 | 2.6 |
| Biomass (odt $ha^{-1}$) | 24.5 | 17.8 | 13.2 | 16.7 | 20 |
| Harvested biomass, total (odt) | 25.2 | 30.7 | 54.5 | 123.1 | 22.6 |
| Turning area, at each end of a row (m) | 3.2 / 7.3 | 4.5 / 8.3 | 5.9 / 5 | 3.4 / 6.7 | 10 / 10 |
| Slope (%) | flat | 15 | 20 | 15 | flat |
| Total working time observed (hours) | 2.7 | 2.2 | 6.0 | 8.5 | 2.4 |

forwards, to allow the stems to get the optimal dropping point on the bed floor, in relation to the elevator conveyor. The angle of the elevator can be changed continuously during harvesting, from a flat angle, when the storage space is empty to a steep angle when the storage is full.

### 3.2 Study Sites

In 2010, 26.4 hours time studies of harvest operations from 5 fields following the cut and storage concept were conducted. An industrial enterprise which cultivates SRC hired the manufacturing company Nordic Biomass to harvest SRC with the harvesting machine "Stemster MK III" (studies 1–4) (chapter 4.2). The harvest was carried out by a very skilled operator who was highly motivated as the enterprise considered buying the machine. The field of study 5 was owned by a farmer who ordered the same machine but from a French contractor. The operator was the contractor himself and he was very familiar with the machine. Land owners and operators agreed that time studies can be conducted. The machines were observed while carrying out their scheduled activity.

Table 1 shows the main data of the time studies and the harvested fields. In fields 1 to 4, three year old poplars and in field 5 three year old willows were harvested, all growing in first rotation. The individual field size ranged from 1–7.4 ha which sums up to an area of 15.4 ha net size from which data were collected, excluding turning area. The turning area is the area at each end of the rows where the machine can turn.

During the harvests of studies 1 to 4 more than 20 cm of fresh snow covered the ground. During the harvest in study 5 the soil was frozen, but almost no snow. Furthermore, the fields of the studies 2, 3 and partially 4 had slopes up to 20% and trees were planted in rows parallel to the slope. The turning area ranged from 2–8 m width, only in study 5 there was a 10 m turning area at each side of the row. Nearly all fields were located at positions exposed to wind and slope.

### 3.3 Data Collection

For the time study data collection, the harvest process was split into working processes with clearly recognizable starting and ending points (e.g. harvesting of one double row, turning or positioning) according to REFA (1991). The time measurement was undertaken with a digital stopwatch. The lengths of the rows and the sizes of the fields were measured by measuring tape and GPS. The amount of harvested biomass was determined by a weigh-bridge which is installed in the harvesting machine. To verify these measurements, values were compared with results of Neubert (2010) who calculated the biomass of the harvested fields (1–4) with special biomass functions. The moisture content of the harvested material was determined in accordance to the ISO standard which means fresh biomass samples were taken and their weight was measured before and after drying for 72 hours at a temperature of 103°C in a ventilated oven (DIN 52 183. 1977).

### 3.4 Description of the Working Processes

In all time studies, the working processes were defined as follows: 1) the tractor drives to a row to start the harvest. 2) The rows are harvested. If a double row system was planted the rows are harvested simultaneously. If the machine's storage space is full, 3) the operator drives to a place where he is supposed to offload the material, preferably at the end of a row. There, 4) the biomass is offloaded and finally, the next cycle begins when the empty machine drives back to the row. The sum of these working processes is defined as productive times (operating hours). Non-productive times were also recorded and consist of all other time consuming working processes or events like e.g. machine breakdowns or organisational delays. Productive and non-productive times sum up to the total working time.

### 3.5 Analyses and Statistics

One recorded disturbance which was longer than 15 minutes (field 4) was excluded from the analysis according to REFA (1991) for not distorting the results of the machine productivity observed. Those time values which belong to the productive working processes and which differ more than 2.5 times from the standard deviation of the respective mean value were treated as outliers and were replaced by the mean value. In the working processes belonging to the non-productive times (e.g. machine disturbance) all values were included.

Statistical analyses of the work studies were processed with Microsoft Excel 2003 and SPSS 19.0. The effects of the following variables on the productivity (odt pmh$^{-1}$) were analyzed by using regression analysis: size of the fields, length of rows and width of turning area, total volume of harvested biomass, tree diameter, plant density and slope. The productivity expressed in harvested hectares per productive machine hour was analyzed against the same variables. The harvesting costs per oven dry ton biomass were calculated using the machine cost calculation scheme of Food and Agriculture Organization of the United Nations (FAO 1992).

# 4 Results

### 4.1 Distribution of Working Times and Volumes

The share of productive working time was 85% of the total working time on average (Table 2). In one case it was more than 98% (study 1) which can be explained mainly by the experience of the driver and the absence of machine breakdowns. Only in study 4, the share of machine breakdowns was relatively high due to problems with the driveshaft of the Stemster. The distribution of the working processes and the share of productive working times are shown in Table 2. The working process <driving to row> could take more than 40% of the productive working time (study 1). Due to short turning areas, the drivers were forced to turn either in long-winded turning manoeuvres (studies 2, 3) or to drive a full turn around the field (study 1).

In study 1, more biomass was collected per load than in the other studies (1.05 odt respectively 0.67 odt) because material was collected from two rows (each 115 m of length) before the driver moved to a defined storage place. This place was chosen to be at each end of the field where a mobile chipper is able to operate. In study 5, 0.87 odt biomass were collected per row. The storage space was not completely full, but collecting additional material from a second row would have been too much material per load. Therefore, material was offloaded after the harvest of each row. Again, the driver was asked to do that at defined places at each end of the rows. In the studies 2, 3 and 4 the volumes per row were too high and the operator therefore was forced to offload biomass in the fields. That was a challenging task and the offloading in the middle of the rows was 1.6 times more time consuming than at the end of the rows. Although not significant, the authors observed that smaller trees got stuck more often during offloading.

On average, 6.4 minutes of working time were needed to cut and store one ton (odt), considering all working processes and 5.6 minutes when only including the productive working processes. A further distribution to each working process is shown in Table 3.

**Table 2.** Distribution of working processes and productive machine hours, per study and in percent.

| Share of working process (%) | Study 1 | Study 2 | Study 3 | Study 4 | Study 5 | Mean |
|---|---|---|---|---|---|---|
| Driving to row | 43.3 | 15 | 25.2 | 9.7 | 15.7 | 21.7 |
| Harvesting | 29.1 | 35.2 | 34.4 | 32.5 | 28.1 | 31.9 |
| Driving to storage | 17.7 | 8.7 | 12.5 | 15.1 | 29.9 | 16.8 |
| Offload material | 8.4 | 17.5 | 17.7 | 16.6 | 12.9 | 14.6 |
| Machine breakdown | 1.5 | 9.9 | 1.4 | 22.6 | 11.8 | 9.4 |
| Others | 0.1 | 13.7 | 8.9 | 3.6 | 1.7 | 5.6 |
| Share of productive times (%) | 98.4 | 76.4 | 89.7 | 73.9 | 86.5 | 85 |

**Table 3.** Required working time per one oven dry ton, in minutes per oven dry ton. N = amount of working plans.

| Study | Parameter | Driving to row | Harvesting | Driving to storage | Offloading material |
|---|---|---|---|---|---|
| 1 | N | 47 | 48 | 24 | 24 |
| | min $odt^{-1}$ | 2.8 | 1.9 | 1.2 | 0.5 |
| 2 | N | 30 | 32 | 27 | 30 |
| | min $odt^{-1}$ | 0.8 | 1.9 | 0.5 | 1.0 |
| 3 | N | 52 | 52 | 52 | 52 |
| | min $odt^{-1}$ | 1.8 | 2.4 | 0.9 | 1.3 |
| 4 | N | 102 | 187 | 119 | 139 |
| | min $odt^{-1}$ | 0.5 | 1.8 | 0.8 | 0.9 |
| 5 | N | 26 | 26 | 26 | 26 |
| | min $odt^{-1}$ | 1.1 | 2.0 | 2.2 | 0.9 |

**Table 4.** Machine productivities of the Stemster MK III, per study.

| Parameter | Study 1 | Study 2 | Study 3 | Study 4 | Study 5 | Mean |
|---|---|---|---|---|---|---|
| ha $pmh^{-1}$ | 0.39 | 0.79 | 0.68 | 0.87 | 0.47 | 0.64 |
| $odt^{-1}$ $pmh^{-1}$ | 9.5 | 14 | 9 | 14.5 | 9.4 | 11.3 |
| $odt^{-1}$ $smh^{-1}$ | 9.3 | 11.3 | 8.1 | 10.7 | 8.1 | 9.5 |

pmh = productive machine hour
smh = scheduled machine hour

### 4.2 Machine Productivity

On average, the productivity of the Stemster MK III was 0.64 ha $pmh^{-1}$ and 11.3 odt $pmh^{-1}$ (Table 4).

Regression analysis showed that the productivity (ha $pmh^{-1}$) was not significantly influenced by the variables size of the field, biomass per hectare and per field, species, length of rows and turning area, tree diameter, plant density or slope. However, in tendency the productivity was higher when turning areas were larger.

### 4.3 Costs

At the moment, only three Stemster MK harvesting machines exist in Europe. One of them can be leased from the manufacturing company Nordic Biomass in Denmark for 200 € $pmh^{-1}$ including tractor and driver plus additional 35 € $h^{-1}$ for waiting times or transports. With regard to an expected increase in cultivation of SRC, the following calculation of machine rates bases on full cost calculations. The investment costs for the Stemster MK III are 215 000 €. The annual utilisation was assumed to be alternatively 200 or 400 hours for the Stemster MK III and 800 hours for the tractor, in this case a standard tractor with an

**Table 5.** Cost calculation for harvesting with Stemster MK III, in € smh$^{-1}$.

| Annual utilisation | € smh$^{-1}$ | € odt$^{-1}$ productivity 9.5 odt smh$^{-1}$ | € odt$^{-1}$ when including chipping |
|---|---|---|---|
| 200h | 330.34 | 34.80 | 54.80 |
| 400h | 223.60 | 23.50 | 43.50 |

investment of 250 000 €. Loan capital was used, the interest rate was 5% and the depreciation period of the machines was assumed to be 8 years. A repair factor of 20% was included according to Nemecek and Kägi (2007). The tractor consumes approximately 25 l diesel h$^{-1}$ according to Nordic Biomass and fuel costs were calculated with 1.14 € l$^{-1}$. Labour cost was set at 20 € h$^{-1}$. Table 5 shows the resulting costs per machine hour and per oven dry ton, calculated with the average productivity of 9.5 odt smh$^{-1}$.

Usually, the stored biomass is chipped some weeks to months after the harvest. Therefore, a mobile chipper is operating independently on the field. It chips the stored trees and blows the chips directly into a container or trailer for transport. Chipping costs are decreasing the more biomass is chipped at one place. According to own experiences, 20 € odt$^{-1}$ are realistic costs for chipping operations which lead to total costs from 43.50 € odt$^{-1}$ to 54.80 € odt$^{-1}$ when using the harvesting machine 400 h a$^{-1}$ or 200 h a$^{-1}$ respectively (Table 5). If similar cost calculations were done with a higher productivity of 15 odt smh$^{-1}$, the resulting harvesting and chipping costs are between 34.90 € odt$^{-1}$ and 42 € odt$^{-1}$, respectively for an annual utilisation of 400 and 200 hours.

To compare the economics with the competing "cut and chip" harvesting system, a similar cost calculation was carried out for a forage harvester equipped with a cutting head for wood. The forage harvester costs 280 000 €. Additionally, the cutting head with an investment of 80 000 € is required. The repair factor of the forage harvester is 20% too and the repair factor of the cutting head is 30%. The fuel consumption is up to 80 l h$^{-1}$. When assuming the same depreciation period (8 years) and the same annual utilisations (alternatively 400 or 200 hours for the cutting head and 800 hours for the forage harvester) harvesting cost result in 16.20–19.20 € odt$^{-1}$. The use of tractors and containers for the transportation of the wood chips is not considered in both cases.

# 5 Discussion

This study presents results of 5 harvesting trials using the Stemster MK III. The average productivity was 0.64 ha pmh$^{-1}$ (Table 4). When including delays average daily productivities of 4.3 ha were reached (assuming eight hours working day). The share of productive working time was 85% (Table 2). Thereof, the driving to row and to storage summed up to 44% on average which is quite high. Often, the machine needed to perform time consuming turnings or drive full cycles around the field before the next row could be harvested due to small turning areas, slopes and unfavourable weather and soil conditions. In study 1, the average time only for driving a full cycle around the field to the next row was 2.8 minutes per ton. That was two times above average (Table 3). When establishing new plantations, the length of both, harvesting machine and tractor as well as the difficulty of the terrain should be considered with adequate turning areas to reduce such long driving times. In general, the driving (both, to the next row and to storage) was 58% of the productive working time when material was offloaded at a defined place that seemed suitable for the subsequent chipping process (studies 1 and 5). In cases where the rows have been so long that there was too much biomass for one load, the drivers offloaded the material in the middle of the rows. The total working time tended to be less in these studies as the driving to the storage place was omitted. However, when it comes to chipping, an additional machine might be required to forward the material from the middle of the plantation to the edge. This problem could be overcome by increasing the capacity of the storage box.

According to the manufacturer Nordic Biomass the predicted productivity of the Stemster MK III is 40 gt pmh$^{-1}$ "when conditions are straight forward" (Nordic Biomass 2011). Experiences from the trials cannot confirm this value as the measured machine productivity varied between

9–14.5 odt pmh$^{-1}$ with an average of 11.3 odt pmh$^{-1}$ (equal to 25 gt pmh$^{-1}$) (Table 4). It should be pointed out that the amount of biomass per hectare was rather low due to marginal site conditions. The average yield of the three year old plantations was 6.1 odt ha$^{-1}$ a$^{-1}$, which is comparably low (Deckmyn et al. 2004). Further, fields 2–4 had slopes up to 20% and plants were planted in parallel to the contour lines for erosion protection reasons which mean high technical challenges for the harvesting operation due to the slope. The productivity was not significantly influenced by the variables size of the field, biomass per hectare, species, length of turning areas, tree diameter, plant density or slope. A reason could be that different aspects influenced the productivity in different studies and the amount of trials was too small. However, it seems realistic to reach higher productivities with the Stemster MK III than in the presented studies because of the following reasons. First it has to be considered that the amount of standing biomass per hectare in the trials was quite low. Second, the size of the turning areas was very small and the drivers were often forced to turn in an unfavourable way or to drive cycles around the field. Third, it was noticed that the conditions were extreme due to slope and weather conditions.

For the calculation of costs alternative degrees of annual utilisation rates were assumed (400 and 200 h a$^{-1}$) as there are only few plantations at present, but an increase in future seems realistic. If the Stemster MK III was used for 200 h a$^{-1}$ the resulting costs for harvesting and chipping are 54.80 € odt$^{-1}$ compared to 43.50 € odt$^{-1}$ in the case of 400 h a$^{-1}$ (Table 5). When assuming a higher machine productivity of 15 odt pmh$^{-1}$, which is still below the manufacturers prediction, harvesting and chipping costs decrease to 34.90–42 € odt$^{-1}$, respectively for 400 and 200 h a$^{-1}$.

Up to now, the harvesting productivity of the Stemster is higher than the productivity of similar machines analysed in earlier studies (Mitchell et al. 1999, Forestry Commission 1998, Danfors and Nordén 1995). The Stemster MK III harvests on average 0.55 ha smh$^{-1}$ while between 0.09–0.22 ha smh$^{-1}$ were reached in earlier trials (Forestry Commission 1998). Newer studies from Caslin et al. (2010) reported 4–6 ha day$^{-1}$ for the rod harvester operating in willow stands. Multiplying our results by an eight hours working day, the productivities are 4.3 ha day$^{-1}$ and therefore in a comparable range. Most of the identified studies analysing the forage harvester system did not report the harvested hectares per working day except Caslin et al. (2010) and Schweier and Becker (2012) who both report capacities up to 6 ha day$^{-1}$.

The productivity (odt smh$^{-1}$) of the cut and storage trials was lower (9.5 odt, equal to 21 gt smh$^{-1}$) (Table 4) compared to forage harvesters (30 gt smh$^{-1}$) and costs were higher. Calculations showed that the production of wood chips results in 3 times higher costs (43.50–54.80 € odt$^{-1}$) when harvesting with the Stemster and including subsequent chipping compared to a forage harvester (16–19 € odt$^{-1}$). However, costs can become more competitive (35 € odt$^{-1}$) if higher productivities are reached with the Stemster because of better site conditions. Delays occurred rarely compared to harvesting operations in the cut and chip system. Spinelli and Visser (2008) as well as Schweier and Becker (2012) report delay factors in the range of 30% for forage harvesters because the machines are dependent of accompanying containers. The high share of productive working time in this study can be explained by the independent working system and the experiences of the operators.

When forage harvesters are used, high efforts in logistics are required as the working progress of the harvesting machine dependents on the accompanying tractors. The produced chips are very fine and have moisture contents (MC) of 50–60%. These chips are not suitable for long term storages (Garstang et al. 2002) and should be used preferably just in time. If the chips can not be used directly, they can be stored only if the MC is reduced to less than 30% (UNI CEN/TS 14961) without causing problems like increase in temperature, fungi development or dry matter losses (Idler et al. 2005, Garstang et al. 2002). In this case, technical drying and storing would be additional processes in the chip supply chain causing additional costs. In contrast, the cut and storage system offers better chips with lower MC and higher heating values.

Stems are cut only, left on the field and dry down by natural seasoning to a MC of less than

30% within a few months. The producer is more flexible in supply as material can be chipped when it is demanded. Transportation costs decrease as the material has a lower MC and transport logistic can be optimised. A higher price can be expected as the calorific value is increased compared to chips with high moisture contents from forage harvesters.

## 6 Conclusion

The study showed that the harvesting alternatives "combined cut and chip" and "chip and storage" can reach harvesting productivities (ha pmh$^{-1}$) in the same range. In the conducted trials the mass related harvesting productivity of the Stemster MK III was lower (9.5 odt smh$^{-1}$) compared to values reported in literature for forage harvesters (15 odt smh$^{-1}$). However, the amount of harvested biomass per hectare was low due to the site conditions (Table 2) and comparable productivities seem reasonable under better conditions. Costs are higher than in earlier studies: overall costs for the procurement of wood chips from cut and storage systems are about 3 times higher than from cut and chip systems. One reason for the higher costs is that existing studies are rather old (Forestry Commission 1998) and cost calculations were updated. For a final evaluation the following advantages in using the cut and storage system have to be taken into account: it offers more flexibility compared to cut and chip systems. Machines like the Stemster MK III offer the option to cultivate SRC especially on those fields where agricultural cultivation systems can not be managed in a profitable way, e.g. due to its possibility to harvest on slopes up to 20–25%. Positive effects especially for fragile soils can be expected as the weight of the machine is lower compared to forage harvesters with accompanying tractors and trailers. The biomass can be chipped when material is demanded. The produced chips have lower moisture contents and therefore increased calorific values. Even though there is no cut and storage harvesting machine (like the Stemster) available on a regular basis at the German market at this moment, the authors see potential for ongoing developments due to promising results of the harvesting trials. With ongoing machine development and improved machines bringing more competition to the market, both systems could become competitive in their economic performances.

## Acknowledgement

This study was undertaken in the framework of the project "Probiopa" (Sustainable production of biomass from poplar short rotation coppice on marginal land) which is funded by the German Ministry for Education and Research (BMBF). The author would like to thank the company Viessmann for allowing data collection and Janus Steng, who wrote his diploma thesis within this topic for supporting the data collection, as well as Uwe Uhlich. Furthermore, the authors thank Staffan Berg for helpful comments on a draft version of the paper. Special thanks are offered to the reviewers.

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