# PRODUCTIVITY OF NEW HARVESTER PROTOTYPE IN WILLOW PLANTATIONS WITH DIFFERENT GROWING STOCK

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**Abstract.** A prototype of a mower-chipper typeharvester was developed for cutting small stems in cooperation between LSFRI Silava and SIA Laflora. The prototype produces chips and eco-pellets of various lengths in short rotation coppice, shelter belts and overgrown agricultural lands. The innovative element of the harvester is use of gravity force (bending of stems by a tractor own weight and formation of bunch of shoots with header and underframe) to feed in circular saws and chipper, thus significantly reducing energy demand for bending of shoots into the chipper, which is the most energy demanding operation in other commercial willow harvesters. Time studies were implemented in Skrīveri region in August 2022 in short rotation coppice fields established in 2011. Willows of tree different ages (1, 3 and 5 years) were harvested. The main factor influencing productivity in the study sites was growing stock of the coppice crops. The driving speed of the base machine cannot be significantly increased to avoid clogging of the chipper infeed and to retain good quality of chips; therefore, reduction of growing stock cannot be compensated with faster driving in the field. It was also noted that wood chip quality becomes significantly worse if the stump diameter of an average shoot is less than 1 cm and the saw blades are more often blocked by thin, flexible shoots. Similarly, clogging related issues were found in the 5 year old plantation. Optimal work conditions were in the 3 year old coppice crop; however, the driving speed of the base machine (MTZ82 tractor) was still too high. The recommended speed in such conditions is 0.8-1.2 $km \cdot h^{-1}$. The yield obtained in the tests under these conditions in the 3 year old coppice crop was 2.4 tons of dry matter per hour. The productivity could be raised by increasing the power of the base machine. There is still space for technical improvements to avoid clogging of material in the chipper and jamming of saw blades, as well as to improve the quality of chips.

**Keywords:** willow, short rotation coppice, harvesting, productivity.

## Introduction

Short-rotation coppice (SRC) is an important potential source of woody biomass for bioenergy with about 30000 ha development prospective in Latvia [1; 2]. Despite the research carried out on several aspects of SRC production, many uncertainties create barriers for the expansion of SRC. One of the key economic sources of uncertainty is harvesting methods and costs; more specifically, the performance of contemporary machine methods is reviewed [3].

Mechanisation of harvest of SRC is a prerequisite to make this source of bioenergy economically and environmentally efficient. Three process lines can be distinguished: trunk wood, bundle, and chopping lines, whereby the latter are the cheapest. In the past, more than 20 different harvesting machines and assemblies were developed for SRC [4], but they have been rarely progressed beyond the prototype stage, and as such they are usually not justifying expectations due to long standby periods during repairs and overestimated productivity projections. In addition to special cutter tools already available for forage harvesters, lower cost mounted assemblies for tractors also have a good chance on the market. However, these still require considerable development and optimising inputs [5]. As production of SRC is a relatively young area of cultivation for farmers, there are only few validated results and experience inputs regarding machinery, despite many development approaches. This experience has been gained from farms in Nordic countries, as well as in agricultural machinery and forestry research facilities in Sweden and in Germany. Mounted units for tractors are being developed and optimised at the University of Göttingen, ATB Potsdam-Bornim and abandoned project from “Salixphere” in Sweden. These can produce good quality rough chips, and can also be used in poplar coppices with rotation periods of 3 to 5 years [6]. Prospective development of baler technology was done in Canada resulting in the industrially applicable harvester [7].

The main requirements for a SRC harvester are sufficient power to be able to manage different size of trees, adjustable height of saw cut, which can be increased by 1-2 cm in each mowing time; and the cutting area should be smooth and small in order to minimize the area of a wound. SRC can also provide various kinds of biofuel: long shoots (up to 8 m long sprouts), bales (pressed, mostly osier wheels), eco-pellets (5-15 cm long billets), as well as the conventional wood chips [8; 9].

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The main shortcomings and issues, which will be addressed by the harvester prototype elaborated in Latvia and tested in this study, are high costs of harvesting equipment and poor adaptability of the existing harvesting solutions to available machinery. High costs of the conventional willow harvesters are determined by multiple factors, including significant power demand (at least 200-300 kW) to bend harvested stems and to feed them into the chipper [10]. To decrease the required capacity (below 100 kW) and, accordingly, costs and fuel consumption, the prototype harvester uses for bending of trees the force of tension of inclined trees. Smaller power demand also leads to reduction of the weight and dimensions of the harvester and ensures possibility to use broader range of farm tractors.

## Materials and methods

Thetime study was carried out in the agroforestry demo site nearby Skrīveri, which was established in 2011 within the scope of the project “Development of establishment and management models of multifunctional deciduous tree and energy plant plantations”.

The plantations were established using a two-row planting scheme – distance between the nearest rows 75 cm, distance between seedlings in rows – 50 cm. The distance between the centres of paired rows is 2.2 m. In practice at the ends of the field the distance between the paired rows often increased, which may be related to peculiarities of the planting technique. If the distance between paired rows is more than 80 cm, especially at the ends of the rows, chipping with the new harvester prototype was difficult, both to form a bunch of shoots to be sawed and during sawing; therefore, at the ends of such rows only one of the paired rows could be cut at the same time. This, in turn, increased the pressure on one side of the saw, because sawing took place with one side of the saw and the stumps of the sawn coppices after leaning back pressed on the saw wheel and periodically jammed the blade. The harvester was effective only in the willow plantation, where both rows could be cut at the same time, using the front part of the saw blade leaving the lowest stumps that did not press from below on the saw blades.

Time studies were carried out in one, three and five-year-old plantations, in which the average length of the shoot is 1.5 m, 3.2 m and 6.3 m, respectively, the number of shoots in the coppice – 16, 8 and 4, and aboveground biomass – 4.5 $\text{tons}\cdot\text{ha}^{-1}$, 16.3 $\text{tons}\cdot\text{ha}^{-1}$and 40.9 $\text{tons}\cdot\text{ha}^{-1}$, accordingly. All trial plots have been harvested at least once before the trial.

The harvester prototype was mounted on a MTZ 82 tractor. The harvester consists of 3 elements – the header, which directs small trees in the front of the machine to a more compacted bundle, the subframe, which is fixed under the tractor, simultaneously covering the less protected parts of the tractor and forming a bundle of shoots for cutting and chipping, and the sawing and chipping compartment with out-feed behind the chipper (Figure 1). Technical specifications of the chipper – mass 2500 kg; length together with the tractor and header 8.8 m; width – 2.5 m; height – 2.8 m; height of the saw above ground – adjustable, from 0.05 m; cutting mechanism – 2 circular saws; saw diameter – 800 mm (according to GOST980); the maximum diameter of the tree to be cut – 100 mm; maximum length of chips – adjustable, up to 50 mm; the required minimum power of the PTO – from 70 kW; required pressure in the hydraulic system – from 200 Mpa; required oil flow in the hydraulic system – from 45 $\text{L}\cdot\text{min}^{-1}$.

The chipper can be adapted to any tractor by appropriately adjusting the subframe and the header. In the study it was adapted to the MTZ82 tractor as part of the experiment.

The harvester is connected to the tractor with a PTO, which transfers power to the saw blades and chipper through a system of gears. In the study, the PTO was set to 600 RPM (in reality up to 500 RPM) and also to 1000 RPM (800-900 RPM in reality). With a 600 RPM the harvester it was able to cut and to comminute small trees, but the chips were longer than 15-20 cm and they had to be chopped again before use. By switching the PTO to 1000 RPM, the quality of wood chips improved, but the employed MTZ 82 tractor clearly lacked power in denser vegetation and the chipper periodically got stuck. Another significant disadvantage of the MTZ 82 is a high driving speed – it could not drive slower than 3 km per hour, but the optimal driving speed during sawing is 0.8-1.2 $\text{km}\cdot\text{h}^{-1}$, so the tractor operator braked the tractor with the clutch, which is not recommended practice in the production conditions. To eliminate this shortcoming, another, more powerful tractor must be used. Another requirement for the tractor is maintaining high (at least 1000 RPM) speed of the PTO shaft at slow driving speed.

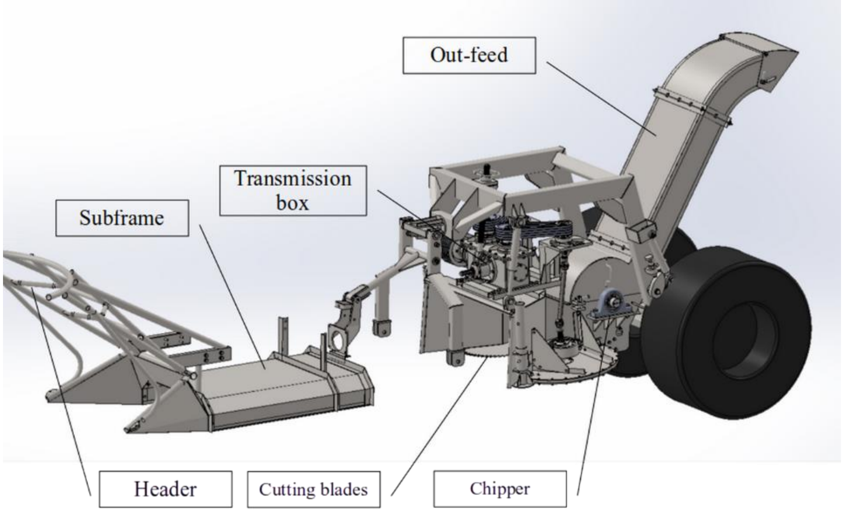

Fig. 1. **Experimental harvester prototype**

Time studies were conducted with shock- and moisture-proof handheld computer, equipped with a specialized program (SDI) for accounting of working time elements and recording time in centiminutes or cmin (1 min. = 100 centiminutes). Measurements were done during field works by counting all working time as described, e.g. in [11]. Harvesting is organized in one shift, i.e. 4-6 working hours during daylight hours. Adjustments, maintenance, cleaning of the chipper and the saw is excluded from the working time, if this consumption of working time is related to the stage of technical readiness. The accounted work elements of working time accounting are given in Table 1.

Table 1

**Harvester time study elements**

| Working time category | No. | Explanation |
|---|---|---|
| Productive time | 1. | Entry into a field/row |
| | 2. | Manoeuvring during work |
| | 3. | Sawing and chipping |
| | 4. | Interruptions to chip sawn material in dense vegetation |
| | 5. | Departure from a field |
| Time not related to direct work | 6. | Non-work activities (talking on the phone etc. performed with the engine running) – the reason is pointed out in notes |

## Results and discussion

Data characterizing the conditions during the time studies, including the number and dimensions of shoots, growing stock and biomass, are provided in Table 2. The average growing stock in the study areas was from 10.1 $m^3$ $ha^{-1}$ in one year old coppice up to 90.8 $m^3$ $ha^{-1}$ in the five-year old plantation.

Table 2

**Input data for productivity calculations**

| Pointer | Unit of measure | Annual shoots | Three-year shoots | Five-year shoots |
|---|---|---|---|---|
| Harvested area | ha | 0.5 | 0.5 | 0.5 |
| Distance between double rows | m | 2.2 | 2.2 | 2.2 |
| Distance between plants in a row | m | 0.5 | 0.5 | 0.5 |
| Average number of rows per area unit | pcs. $ha^{-1}$ | 44 | 44 | 44 |
| Number of cuttings planted | pcs. $ha^{-1}$ | 17424 | 17424 | 17424 |
| Survival rate | - | 95% | 80% | 70% |

Table 3 (continued)

| Pointer | Unit of measure | Annual shoots | Three-year shoots | Five-year shoots |
|---|---|---|---|---|
| Average plants per area | pcs. ha$^{-1}$ | 16553 | 13939 | 12197 |
| | pcs. m$^{-1}$ | 3.8 | 3.2 | 2.8 |
| Average driving distance | km·ha$^{-1}$ | 4.4 | 4.4 | 4.4 |
| Number of shoots per coppice | pcs. | 16 | 8 | 4 |
| Height of average shoot | m | 1.5 | 3.2 | 6.3 |
| Diameter of average shoot at root neck | cm | 0.8 | 1.8 | 3.2 |
| Volume of average shoot | m$^3$ | 0.00004 | 0.0003 | 0.0019 |
| Volume of average coppice | m$^3$ | 0.0006 | 0.0026 | 0.0074 |
| Average growing stock | m$^3$ ha$^{-1}$ | 10.1 | 36.1 | 90.8 |
| | m$^3$ m$^{-1}$ | 0.002 | 0.008 | 0.021 |
| Basic wood density | tons m$^{-3}$ | 0.45 | 0.45 | 0.45 |
| Average biomass (dry mass) | tons·ha$^{-1}$ | 4.5 | 16.3 | 40.9 |
| | tons m$^{-1}$ | 0.001 | 0.004 | 0.009 |
| Average biomass increase | m$^3$ h$^{-1}$ yr$^{-1}$ | 10.1 | 12.0 | 18.2 |
| | tons h$^{-1}$ yr$^{-1}$ | 4.5 | 5.4 | 8.2 |

A summary of time studies and productivity indicators is given in Table 4. Long interruptions related to equipment repairs are excluded from the work time and will not affect productivity when all the shortcomings typical for prototypes have been eliminated in the harvester prototype and optimal settings for various nodes have been obtained. The average driving speed decreases with the growth of biomass and under optimal conditions in a five-year plantation it should be even lower, but technically it could not be achieved while simultaneously maintaining high PTO speed.

During the studies 4.4-6.8 hours per ha were consumed, depending on the age of the coppice. The older is the plantation and the bigger growing stock, the greater the consumption of the work time. If converting to loose volume (LV) cubic meters, production costs increase from 1.8 € LV m$^{-3}$ in five-year-old coppice to 10.6 € LV m$^{-3}$ in one-year-old plantation. Despite the significant cost reduction in the five-year-old plantation, the output power and other characteristics (minimum movement speed while maintaining high PTO revolutions) of the selected base machine are not suitable for sawing five-year-old coppice, which is already overgrown. In such plantations it is possible to increase the productivity, if the thickest shoots are cut with a brush cutter before mechanized harvesting.

Table 4

**Calculation of harvester productivity**

| Pointer | Unit of measure | Annual shoots | Three-year shoots | Five-year shoots |
|---|---|---|---|---|
| Driving speed during work | km·h$^{-1}$ | 1.2 | 0.9 | 0.8 |
| Weighted average time to enter a field | cmin | 600 | 600 | 600 |
| Entering row | cmin | 450 | 550 | 900 |
| Manoeuvring during operation | cmin | 400 | 600 | 1000 |
| Interruptions | cmin | 220 | 440 | 660 |
| Weighted average time to leave a field | cmin | 600 | 600 | 600 |
| Work time consumption per 1 ha | | | | |
| Weighted average time to enter a field | hours | 0.2 | 0.2 | 0.2 |
| Entering row | hours | 0.2 | 0.2 | 0.3 |
| Harvesting time | hours | 3.7 | 4.9 | 5.5 |

Table 5 (continued)

| **Pointer** | **Unit of measure** | **Annual shoots** | **Three-year shoots** | **Five-year shoots** |
|---|---|---|---|---|
| Manoeuvring during operation | hours | 0.1 | 0.2 | 0.3 |
| Interruptions | hours | 0.1 | 0.1 | 0.2 |
| Weighted average time to leave a field | hours | 0.2 | 0.2 | 0.2 |
| Total work time consumption | hours | 4.4 | 5.8 | 6.8 |
| Productivity | $m^3 \cdot h^{-1}$ | 2,3 | 6.2 | 13.4 |
| | $tons \cdot h^{-1}$ | 1.0 | 2.8 | 6.1 |
| Efficiency (actual work time) | - | 85% | 85% | 85% |
| Adjusted yield | $m^3 \cdot h^{-1}$ | 1.9 | 5.3 | 11.4 |
| | $tons \cdot h^{-1}$ | 0.9 | 2.4 | 5.1 |
| Hourly cost of work | $EUR \cdot h^{-1}$ | 48 | 48 | 48 |
| The density of the pile of chips | $LV\ m^3 \cdot ton^{-1}$ | 5.2 | 5.2 | 5.2 |
| Production costs | $EUR \cdot m^{-3}$ | 24.8 | 9.1 | 4.2 |
| | $EUR \cdot ton^{-1}$ | 55.0 | 20.2 | 9.3 |
| | $EUR \cdot LV\ m^{-3}$ | 10.6 | 3.9 | 1.8 |

The most important factor affecting productivity, as well as the limiting criterion for the application of the technique, is the growing stock (Figure 2). The harvester is optimally applicable in the three-year-old coppice, although a more powerful tractor is still needed. The design of plantation is also important – the distance between the rows in a double-row planting should not be more than 75 cm. It is probably useful to cut the shoots at the ends of the rows with a brush cutter to make it easier for machinery to enter the field.

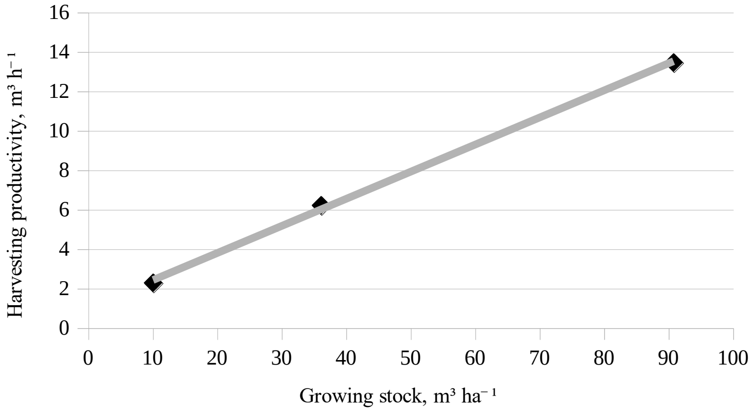

Fig. 2. **Relationship between productivity on growing stock**

Most of the work time is spent for sawing, but as the age and the dimensions of the coppice increases, the consumption of time for entering the rows and manoeuvring increases, as well as the total duration of interruptions to release the saw blade or the chipper (Figure 3).

The cost of chip production according to the hourly cost of the equipment is from 10.6 $EUR \cdot LV\ m^{-3}$ in the one-year-old coppice to 1.8 $EUR \cdot LV\ m^{-3}$ in the five-year-old coppice. However, more realistic indication of the prime cost is acquired in the three-year-old plantation – 3.9 $EUR \cdot LV\ m^{-3}$, because in older coppice, at least at the moment, the capacity of the equipment is insufficient for long-term operation.

The research concluded that the harvester prototype performs its functions and is suitable for cutting willow plantations if the willow shoots are up to 3 years old and on average 3 m long. Working with larger willows requires rebuilding and widening the header and the subframe. The throughput of saws and chippers seems to be sufficient if the PTO provides constantly high revolutions.

Fig. 3. **Distribution of working time elements, depending on the age of the shoots to be cut**

Trials have shown that the placement of stems is of critical importance in the sawing process, and the machine is not yet ready for continuous cutting and chopping of natural vegetation. The main problem is the jamming of the saw blades when stumps of the felled stems are cut with the edge of the saw instead of the central part of the saw blade. This problem can be solved by replacing circular saws with chain saws. This approach is used in the Bracke C.16 harvester cutting head. An alternative solution is the use of a free-hanging chain (the approach implemented in Bender harvester), however, this solution has not proven to be viable.

The initially proposed base machine MTZ82 is not suitable for the harvester, because the driving speed of the tractor at the optimal PTO rotation speed is too high and cannot be reduced, so the harvester prototypes intended for production should be built for more powerful machinery, choosing tractors with the lowest possible movement speed at the optimal PTO rotation speed. The speed of the PTO should be at least 1000 RPM in order to obtain high-quality wood chips. By reducing the rotation speed, the length of the chips increases, and at 500 RPM, chips are no longer formed, but partially scarified shoots are extracted from the chipper. The possibilities of adjusting the length of the chips by changing the rotation speed of the chipper or the protrusion of the knife blades are limited, because the protrusion of the knife blades significantly interferes with the pulling of the shoots into the chipper and the formation of jams above and below the saws. An alternative solution is to rebuild the transmission by changing the size of the gears going to the saws and chippers, although this solution has not been tested in practice.

The most significant potential improvement of the harvester is the replacement of circular saws with chain saws. This improvement would allow the harvester to be used in natural vegetation; however, that can double the cost of a harvester and increase its maintenance costs. Other improvements, partially implemented during the trials, is increase of the thickness of the counter-knife plate to reduce the protrusion of the chipper knives and prevent the risk of the counter-knife bending; the header can be lowered to cover even relatively wide coppices, especially at the ends of the rows. An alternative solution is to increase the width of the header, but this will make it difficult for equipment to move on the roads and reduce efficiency in low bushes. The subframe must be adapted to the base machine, so that it does not limit the manoeuvrers of the equipment. The mounting points of the rotor of the chipper should be improved by increasing its resistance under increased load.

Other researchers in the Baltic region, e.g. [12], demonstrate significantly bigger production costs (43…45 $\text{EUR}\cdot t_{dm}^{-1}$ for mower-chippers and forage harvesters and 64…72 $\text{EUR}\cdot t_{dm}^{-1}$ for the whole shoot harvesters), which can be explained by significantly bigger investments and by limited availability of harvesters affecting the service costs, while other researchers reported several times smaller production costs, e.g. [13] reported 12.27 $\text{EUR}\cdot t_{dm}^{-1}$ cost for Auger chipper (‘Göttinger’) and [14] reported

15.30…21.50 EUR·$t_{dm}^{-1}$ for ATB mower-chipper. These cost estimates are more relevant to our findings. Another review article [15] reports very diverse cost estimates by different researchers – from 6 to 99 EUR·$t^{-1}$of fresh material. The mower-chipper type harvesters evaluated in this study required tractors with at least 100 kW engine (342 in average) pointing out that our bending solution really helps save power. Comparison of mower-chipper and forage harvesters [6] concludes that the driving speed can be increased to 3-5 km·$h^{-1}$; however, it requires more massive construction of the harvester and direct transmission should be replaced with hydraulic transmission.

## Conclusions

1. The hypothesis of the study – the use of a sub-frame for forming a bundle of wood and feeding material into the chipper reduces the power of the machinery required for harvesting of coppice – has been confirmed. Replacing the solution of "bending in" shoots with tilting reduces the power of the equipment recommended for cutting coppice by up to 3 times and MTZ82 can be sufficiently effective in harvesting of up to 3-year-old shoots.
2. Harvesting of coppice requires tractors, which can drive slowly (down to speed of 0.5 km·$h^{-1}$, while retaining the PTO speed of at least 1000 RPM). Harvesting of naturally developed bush lands requires significant improvements (replacing the sawing mechanism with a chain saw to prevent the cutting compartment from jamming).
3. After solving minor technical issues identified during the study the developed solution is recommended for practical use in young willow and poplar SRC, especially in single-row plantations, but a more powerful base machine must be used.

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## Author contributions

Conceptualization, A.L.; methodology, A.L. and K.M.; software, A.Z.; investigation, A.Z., I.G. and G.G.; data curation, A.A., V.B. an J.I.; writing – original draft preparation, K.M.; writing – review and editing, A.L. and A.Z.; project administration, A.L. All authors have read and agreed to the published version of the manuscript.

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