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Climate change mitigation potential of trees in shelter belts of drainage ditches in cropland and grassland

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Latvian State Forest Research Institute SILAVA

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REPORT

Report on productivity and costs of recommended (“site type” and “plant community” specific) mechanization solutions for shelter belts

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ANNOTATION

The aim of the study is selection of the most suitable solutions for mechanized planting, early tending and harvesting of the shelter belts conforms with criteria for industrial research resulting in identification of the most appropriate mechanization solutions for management of woody crops in shelter belts in relevant environment. Within the scope of the study we evaluated existing mechanization solutions, elaboration of work methods adopted for the shelter belts. The identified technologies are evaluated according to productivity, cost and GHG emissions. The considered management stages are soil scarification, planting, tending, harvesting, biomass production and delivery. We started with elaboration of scientific substantiation of mechanization systems for the shelter belts including soil scarification, planting, tending, thinning where necessary, harvesting and regeneration, based on literature review and productivity studies in willow plantations and fast-growing poplar stand. We summarized information on average productivity of different harvesting solutions in database providing possibility to estimate GHG emissions. Cost calculations still needs to be adopted considering significant changes in fuel, salary and other costing positions during the previous year.

This report focuses on the scientific basis of mechanization systems for the shelter belts, including soil scarification, planting, weed control, thinning and regenerative logging. We assessed mechanization solutions according to different types of vegetation. The plant groups are not divided since the technologies can be grouped into single tree and multi-stem processing technologies and planting of short cuttings, long cuttings and container seedlings. Manual planting of bare-root seedlings is not considered since it still cannot be efficiently mechanized. We evaluated the logging technology according to the target assortment, focusing on the so-called CTL (cut-to-length) technology and the preparation of the wood chips directly in the field. We also identified the need to increase the distances between trees in comparison to initial recommendation so that the area can be used to produce fodder during the early development years.

CONTENT

Images and graphs

Tables

1 INTRODUCTION

One of the preconditions of efficient management of the shelter belts is mechanization of the whole process utilizing machinery, which is already available in rural regions, e.g. farm tractors and specialized harvesting and planting solutions. We evaluated the whole process to identify cost and GHG footprint of available mechanization solutions, from planting to harvesting. Mechanization can play a valuable role in the management of woody shelter belts. By using machines, farmers can plant, manage, and harvest shelter belts more efficiently and cost-effectively. This can help to improve the productivity of agricultural land and to protect the environment.

Mechanized planting of woody shelter belts is becoming increasingly common, as it can be more efficient and cost-effective than manual planting. There are a number of different machines available for planting shelter belts, including:

- tree planters: these machines are designed to plant trees in a straight line, at a specific spacing.
- seeding machines: these machines are used to sow seeds of woody plants into the ground.

The type of machine that is used for planting will depend on the size and shape of the shelter belt, the type of plants being planted, and the budget available (Zhu 2008).

Once a woody shelter belt has been planted, it is important to manage it properly in order to ensure that it grows and functions effectively. Some of the most important management tasks include:

- weed control: weeds can compete with trees for water, nutrients, and sunlight, so it is important to control them regularly.
- pruning: pruning is important to maintain the health and shape of trees, and to prevent them from becoming overgrown.
- pest control: pests can damage or kill trees, so it is important to monitor for pests and to take action to control them if necessary.

Woody shelter belts can be harvested for a variety of purposes, including:

- timber production: trees in shelter belts can be harvested for timber, which can be used for construction, furniture, and other purposes.
- biomass production: trees in shelter belts can be harvested for biomass, which can be used to generate energy or to produce other products.
- recreation: shelter belts can be harvested for firewood, which can be used for cooking, heating, and other purposes.

The type of harvesting that is used will depend on the purpose for which the trees are being harvested.

Short-rotation coppice (SRC) is an important potential source of woody biomass for bioenergy with about 30000 ha development prospective in Latvia (Lazdina et al. 2007; Makovskis et al. 2021). 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 supply of bioenergy economically and environmentally efficient. Three system traces may be distinguished: single stem, bundle and on-site chipped biomass, wherein the latter are the cheapest. In the past, more than than 20 one-of-a-kind harvesting machines and assemblies had been advanced for SRC (Pecenka et al. 2014), however they had been hardly ever stepped forward past the prototype stage, and as such they may be typically now no longer justifying expectancies because of lengthy standby durations throughout maintenance and hyped up productiveness projections. In addition to bush-cutting equipment already available for forage harvesters, lower value assemblies for tractors additionally have a good chance at the market. However, those nevertheless require significant improvement and optimising inputs (Scholz & Lücke 2007). As manufacturing of SRC is notably younger area of cultivation for farmers, there are only few verified results concerning equipment, notwithstanding a huge variety of improvement approaches. This development has been moved on in farms in Nordic countries, in addition to in agricultural equipment and forestry studies centres in Sweden and Germany. Mounted devices for tractors are being advanced and optimised on the University of Göttingen, ATB Potsdam-Bornim and abandoned undertaking from “Salixphere” in Sweden. These can produce properly first-rate wood chips, and also can be utilized in poplar coppices with rotation durations of three to five years (Ehlert & Pecenka 2013). Prospective improvement of baler technology become executed in Canada ensuing withinside the industrially relevant harvester (F. Lavoie et al. 2008).

The predominant necessities for a SRC harvester are enough power on the way to control one-of-a-kind length of bushes, adjustable height of cut, which may be multiplied with the aid of using 1-2 cm in every mowing time; and the slicing place sought to be clean and small a good way to reduce the area of a wound. SRC also can offer numerous varieties of biofuel: lengthy shoots (up to eight m lengthy sprouts), bales (pressed, normally osier wheels), eco-pellets (five-15 cm lengthy billets), in addition to the traditional wooden chips (Kofman & Spinelli 1997; Lazdiņa et al. 2007).

The predominant shortcomings and issues examined on this study, are excessive prices of harvesting system and insufficient adaptability the prevailing harvesting solutions to to be existing equipment. High prices of the traditional willow harvesters are determined with the aid of using more than one factors, inclusive of huge power demand (at the least 200-300 kW) to bend harvested stems and to feed them into chipper (Berhongaray et al. 2013). To lower required capacity (beneath 100 kW) and, accordingly, prices and fuel consumption, we tested prototype harvester developed in Latvia, which use for bending of bushes the pressure of anxiety of willing bushes. Smaller power demand leads to reduction of required weight and dimensions of the harvester and guarantees opportunity to apply broader variety of farm tractors. In addition, to evaluate possibility to use compact class harvesters for application of cut-to-length harvests in shelter belts.

2 METHODOLOGY

Within the scope of the study, several aspects of mechanization have been evaluated for all stages of management of shelter belts. Mechanization solutions are divided into 3 groups – grass, bush and woody crops. Mechanization solutions are evaluated according to the following indicators:

1. application of techniques – what operations are carried out in connection with woody shelter belts in shelter belts;
2. application of the technique – seasonality, sequence of application in economic activity when managing woody crops;
3. brand and model of the technique – the name of specific models or a summary characteristic, for example, a middle-class harvester, which describes a typical situation in the execution of the operation in question;
4. base machine – if necessary, also mentioning that the base machine can be used with several technical units included in the list;
5. requirements for the base machine – power, drive mechanism, other requirements;
6. fuel consumption – per working hour or per 100 km;
7. lubricant consumption – lubricants used and their consumption per working hour (this is complicated position since very limited information is available while contribution to costs and GHG emissions is less than 10% of the total values);
8. dimensions of the machine – length, width, height, mass, width of the working lane and its limitations (minimum required width);
9. costs – purchase fees, depreciation period in working hours or years, maintenance costs, including equipment and materials;
10. taxes and insurance – annual costs;
11. other costs – annual costs, such as training of employees, daily allowance, stay in the field;
12. technical workload – readiness, working days per year for the specific type of equipment application;
13. shifts – in the record, the practice of shifts (number per day and duration), the number of operators engaged in the technique;
14. productivity – ha or units of output in the working hour;
15. factors affecting productivity – characteristics of the impact; limit values for the application of the technique, e.g. where possible, equations for yield calculations;
16. alternative uses – other uses of machinery, including base machinery, e.g., in agriculture or construction, particular attention should be taken on the impact

of the seasonality of works on the availability of machinery and the competition between different applications;

17 alternative solutions – techniques that can replace this technical unit, analysis of seasonal availability and other advantages and disadvantages;

18 availability of equipment in Latvia – whether the equipment is available, whether it is rare or popular enough;

19 related technical units – a technique necessary to ensure the full range of machinery, indicating, if necessary, specific technical units from the list, if their use is determined, for example, by the dimensions of the machine;

20 sources of information – information provided by dealers, farmers or logging companies.

Tasks to be covered by the analysis of the sowing and management of undergrowth vegetation:

1) soil preparation;
2) sowing of grass mixtures;
3) application of plant protection products;
4) early management and weed control;
5) mowing grasses;
6) compacting and other picking solutions;
7) forwarding grass from the field;
8) seed production.

Tasks to be covered by the analysis of establishment and management of bushy crops (willows):

1) soil preparation;
2) planting;
   - short cuttings,
   - long cuttings,
   - container seedlings,
   - bare-rooted seedlings,
3) early care, mulching of space between rows;
4) harvesting and grinding of biomass;
5) restoration of plantings, milling of stumps.

Tasks to be covered by the analysis of establishment and management of woody crops:

1) soil preparation;
2) planting short cuttings;
3) planting container seedlings plants;

4) planting long cuttings;
5) planting of bare-rooted seedlings;
6) sawing, delimbing and bucking of individual trees for the production of logs;
7) forwarding roundwood and logging residues;
8) stump forwarding for restoration of re-cultivated area;
9) chipping and delivery of the mowed woody vegetation with a self-propelled chipper with a manipulator and cargo compartment;
10) shredding of the residues and low quality logs at roadside with a diesel chipper;
11) crushing of stumps at roadside;
12) shredding of round timber at a customer side with an electrically operated chipper;
13) delivery of round timber by timber trucks;
14) delivery of chips by chip hauler;
15) extraction of stumps for the renewal of protection zones;
16) loading of crushed material.

3 EVALUATION OF MECHANIZATION SOLUTIONS

3.1 Sowing of undergrowth vegetation

Soil preparation – continuous plowing and cultivation simultaneously with the treatment of the rest of the territory. For plowing before planting, an agricultural tractor is used, most often with a 4-body plow with a working width of 1 m, the cost of the service in 2021 was 52 € ha^{-1}, including indirect costs[1].

Pre-sowing cultivation with an agricultural tractor, cultivator width 5 meters, service cost in 2021 was 32 € ha^{-1}, including indirect costs[1].

Sowing grasses in a woody shelter belts in shelter belts of different widths is carried out in the spring in the period from late March to early May, depending on weather conditions. For sowing, you can use, for example, Einbock PNEUMATICSTAR, a grass pneumatic seeder (Figure 1) designed for sowing grasses. Seeders for sowing lawns are available from various types (discs, boots, with a forcing roller, harrow plow, etc.) from the manufacturer. For sowing lawns, you can use seeders from different manufacturers and combinations intended for sowing grain – combined. Here, too, there are many options that can be used. The base machine is an agricultural tractor. Power depends on the trailed or towed unit, starting from 30 hp. Drive with PTO (540 rpm). Fuel consumption 12-22 L ha^{-1}, depending on the tractor and the unit attached to it. Lubricant consumption, depending on the technical unit 0.1-1.0 kg. Dimensions of the aggregate from 2 to 12 meters for pure grass seeders and from 2 to 6 m for various types of combined seeders. For woody shelter belts seeders should be selected so that they correspond to the bandwidth of woody plants and can easily maneuver, i.e., seeders should be up to 4 m wide. Purchase cost starting from 1500 €. The largest cost is for combined seeders with a large working width. The period of use of the technique, depending on the type of farming and the size of the farm, is 4-30 days a year. Productivity ranging from 0.5 ha h^{-1} up to 6 ha h^{-1}. In woody shelter belts, smaller productivity should be taken into account. Yield is affected by weather conditions, the quality of soil preparation, soil moisture and bearing capacity. A wide range of units for sowing grasses are available in Latvia and various technical solutions are available.

[1]HTTp://new.llkc.lv/sites/default/files/baskik_p/pielikumi/3.tabula_3.pdf

Figure 1. Einbock PNEUMATICSTAR seeder[2].

Application of plant protection products shall be avoided on grasslands, except in the case of cover crops.

Early care involves the harrowing of grasses in line spacing. The work is carried out in the spring – March to the end of April. For harrowing, you can use, for example, Einbock AEROSTAR / GRASS MANAGER (Figure 2). The offer in Latvia is very big. The most suitable for Latvia in terms of price and adaptability to different base machines are harrows produced in Poland. The base machine is an agricultural tractor, power 25-130 hp. Fuel consumption 10-18 L ha^{-1}. Harrows in most cases are not lubricated, except for harrows in which the sides rise with cylinders, lubricant consumption 0.1 kg per day. In woody shelter belts there is no need for such harrows. Working bandwidth 2-12 m. For woody shelter belts suitable harrows 2-4 m wide. The price of harrows 800-15000 €. Harrowing is used, depending on the farm's size, up to 10 days a year. Productivity 2-8 ha h^{-1}. Yield is determined by the terrain of fields, configuration, stones. A wide range of harrows and various technical solutions are available in Latvia.

Einbock AEROSTAR[3]

GRASS MANAGER[4]

Figure 2. Grass harrowing.

[2]https://www.einboeck.at/en/products/grassland-care/grassland-seeder
[3]https://www.einboeck.at/en/products/crop-care/weeding-technology/aerostar-exact
[4]https://www.einboeck.at/en/products/grassland-care/grassland-weeder/grass-manager

Mowing grass can be carried out in a woody shelter belts in line spacing. Mowing time – from May to the end of June, as well as from the beginning of September to the end of the month. In woody shelter belts, mowing is possible up to 5 years after planting, until the crowns of the trees have expanded and the grass biomass has production has been significantly reduced. Mowing is possible only between strips of woody plants, since the bushes are planted too densely for mowing between them. Mowers from various manufacturers are available on the market, such as Krone, Samasz, Pottinger, etc. Base machine ir agricultural tractor with a capacity of 80-130 hp. Fuel consumption 15-20 L ha^{-1}. Lubricant consumption 0.2-1.0 kg per day. Working bandwidth 1.2-12 m. In woody shelter belts, it is useful to use a mower that is slightly wider than a tractor, so that it can be used to navigate the line spacing and turning points. It is important that the mower is attached behind or in front of the tractor and not on the side, because the side attachment requires twice more space. The price of the mowers is 1500-25000 €. Depending on the size of the farm, the mower is employed up to 30 days a year. Productivity is 1.5-8 ha h^{-1}. The productivity is determined by the terrain and configuration of the fields. Depending on the target product, grasses use different types of trailers for bundles or pressed hay for removal from the field.

3.2 Establishment and management of bushy compartments of shelter belts

Before preparing the soil, plowing is carried out, as described in the previous chapter. For plowing agricultural tractor is used. The cost of the service in 2021 was 52 € ha^{-1}. After plowing, the area should be cultivated to improve the structure of the soil. The cost of cultivation in 2021 was 32 € ha^{-1}. Plowing is carried out in autumn, cultivation – in autumn or spring. Soil preparation for planting grasses, willow and woody plants is carried out simultaneously, in a continuous order.

In willow plantations it is common to use used short cuttings (sometimes called pellets), which are planted with specialized machines. Cuttings are planted in the spring, as soon as the machines can move over the field. HSAB Two Row Billet Planter base machine is an agricultural tractor with an engine power of at least 80 hp. Mass 2.2 t, length 2.35 m, width 4.05 m, height 2.35 m, bunker volume 2 m^3, planting density 5-10 cuttings per meter, working speed 8-10 km h^{-1}, effective working width 4 m. Shift includes a tractor driver and 2 workers. Consumption of planting material 2 LV m^3 of cuttings per hectare, planting rate 1 ha h^{-1}. The yield is significantly affected by the moisture of the soil, the size, configuration and planting thickness in the field, the power of the tractor (the best indicators if it is >150 hp). In Latvia, this solution has no practical application yet.

Figure 3. Cuttings seedling machine[5].

[5]http://salixab.se/userfiles/files/hsab_billet_planter_with_granule_spreader.pdf

Longer cuttings (15-20 cm) are used for establishment of willow plantations in the most of the cases. Cuttings are cut by seedling directly during planting. Willow cuttings are planted in the spring after soil preparation. One of the common models of planting machines Egedal Energy Planter (2-row planter). The base machine is an agricultural tractor. The yield of the hydraulic system is at least 60 liters per minute, engine power of at least 80 hp, two-row (1 double-row) planter has a mass of 1.6 t, a distance between rows of 0.75 m and between double rows 1.5 m. Working width of one pass is 2.25 m. The price of the seedling machine in 2021 was 61515 €. One tractor driver and 1 worker work in the shift. Providers usually arrange 1 shift. Seedling productivity is around 1.5 ha h^{-1}. Productivity is significantly affected by the quality of soil preparation. The official distributor of Egedal in Latvia is SIA Silja. Delivery time 15-16 weeks. There are already several machines working in the Baltic region and this technology can be considered as mature and ready for commercial utilization.

Figure 4. Two-row cuttings seedling machine[6].

A two-row planter is best suited for woody shelter belts in shelter belts, but in the case of wider bands, a four-row planter can be used for greater productivity (Figure 5). Minimum requirements for the productivity of the hydraulic system 60 liters per minute. $^{-1}$; engine power of at least 80 hp. The mass of the seedling machine is 2.8 t, the width between the rows in the double row 0.75 m, between the rows 1.5 m. Working width of one trip 4.5 meters. The price of the seedling machine in 2021 was 107141 €. One tractor operator and 2 workers work in the shift. Yield 3 ha h^{-1}. Yield is affected by the quality of soil preparation and field configuration. Official Egedal distributor in Latvia SIA Silja. Delivery time 15-16 weeks. At least 1 machine worked in the Baltic States in 2021.

[6]https://egedal.dk/en/produkter/energy-planter

Figure 5. Four-row cuttings plantain[7].

An alternative solution for planting long cuttings is the Salix Maskiner Step planter planting machine. The base machine is an agricultural tractor, the recommended power of at least 105 kW. Equipment width 4 m, length 2 m, mass 1.8 t. The plant consists of 1-3 double-row segments, in the literature more often mentioned 4-row (2 double-rows), the distance between the cuttings in double rows 0.76 m, the width of the single-row strip is 4.88 m. Planting density is 13450 seedlings ha^{-1}. New equipment is not available, used equipment price ranges from 16000 to 40000 €. The tractor operator and 2 workers work in the shift. Productivity is 1.14 ha h^{-1}. The productivity is affected by the speed of laying the cut-offs, the regulation of the planting machine, the quality of the planting material, soil moisture etc.

3.3 Establishment and management of woody shelter belts

Planting machines for cuttings described in the previous chapter can be used to plant a compartment of trees in shelter belts, but a container seedlings and bare-rooted seedlings is also possible for mechanized planting. Container seedlings can be planted, for example, with the planting of the planting machine Risutec APC (Figure 6). The base machine is an excavator. Excavator mass at least 14-20 tons, pressure in the hydraulic system at least 125 bar, hydraulics flow a minimum of 100 L min. $^{-1}$, fuel consumption on average 9.5 L h^{-1}. The mass of the equipment 1.8 t. Price in 2021 was 80000 €. The cost of repair and maintenance is 6 € h^{-1}. The machine is usually serviced by 1 operator. Yield averages 196 seedlings per hour (Laine & Saarinen 2014). At least 1 machine is working in Latvia.

[7]https://egedal.dk/en/produkter/energy-planter

Figure 6. Risutec APC Planter[8].

M planter M240 is an alternative solution with 2 planting heads. The base machine is an excavator with a mass of 14-20 tons, a pressure in the hydraulics system of at least 170 bar, a hydraulics flow of 100 L min.$^{-1}$, fuel consumption 9.5 L h^{-1}. The mass of the equipment 2.8 tons. The price of the equipment in 2021 was 45000 €, the cost of repair and maintenance is 5 € h^{-1}. The machine is serviced by 1 operator. The productivity is 280 seedlings per hour (Liepins et al. 2011).

Figure 7. M planter M240 seedling machine[9].

An alternative solution with 1 planting head is Bracke P11, which is also mounted on an excavator with a mass of 14-20 tons, a pressure in the hydraulics system of at least 125 bar, a hydraulics flow of 100 L min.$^{-1}$, fuel consumption 9.5 L h^{-1}. The mass of the planter is 1.1 t, the capacity of the seedling carousel is 196 seedlings. The price of the equipment in 2021 was 45000 €, the cost of maintenance and service is 5 € h^{-1}. The plant is serviced by 1 operator, productivity 244 seedlings per hour (Laine & Saarinen 2014).

[8]https://www.youtube.com/watch?v=8FmE2w3rQE4
[9]https://www.agromaster.lv/jauna-tehnika/m-planter/

Figure 8. Bracke P11 planting machine[10].

For planting bare-rooted seedlings in 1 row in prepared or unprepared soil Egedal Transplanter OK is available. Base machine – an agricultural tractor with an engine power of at least 80 hp. The mass of the equipment is 1.4 t. Planting lane – 1 row, width depends from tractor width. Prices in publicly available sources for used machines are 6-9 thousand €. The equipment is serviced by a tractor driver and 1 worker. Productivity 200-750 seedlings per hour. Productivity is affected by the quality of soil preparation. All kinds of bare-rooted seedlings can be planted, but initially the plant was built for planting Christmas trees, respectively, the equipment is convenient to apply in woody shelter belts in agricultural soils[11].

For planting bare-rooted seedlings in 2 rows, Egedal Transplanter Type K can be used (Figure 9), which is also assembled on an agricultural tractor with an engine power of at least 80 hp. The mass of the two-row planter is 1.3 t, width is 2.5 m. Prices for equipment are not available, the price of used equipment is 6-9 thousand €. The equipment is serviced by a tractor driver and 2 workers. Productivity in the Christmas plantation is 1200-2000 seedlings per hour. Productivity is affected by the quality of soil preparation, planting thickness, the complexity of the field. Both coniferous and deciduous seedlings can be planted with the plant. The maximum distance between the rows is 170 cm, which may not be enough in a woody shelter belts.

[10]https://www.brackeforest.com/products/planters-seeders/165-bracke-p11-a-planting-machine
[11]https://pdf.agriexpo.online/pdf/egedal-maskinenfabrik/transplanter-type-ok/176284-6081.html#open22676

Figure 9. Egedal Transplanter Type K planting machine[12].

Another solution for arranging a 2-row plantation Egedal Transplanter Type Hydromatic, assembled on an agricultural tractor with an engine power of at least 80 hp. The mass of the two-row planter is 1.2 t, width is 2.5 m, the maximum distance between rows is 130 cm. The equipment is serviced by a tractor driver and 2 workers. Productivity 2500-3000 seedlings per hour. Productivity is influenced by the quality of soil preparation and the complexity of the field. Both conifers and deciduous trees can be planted. The small distance between the rows limits the application of this plant in woody shelter belts.

Another planting device of the same manufacturer is Egedal Trans planter Types JT. For this machine, the distance between the rows is 165 cm, but it can be increased by transforming the machine. The equipment must be mounted on an agricultural tractor with an engine power of at least 80 hp. The mass of the two-row planter is 0.6 t, width 2 m (in the absence of special rebuilt), length 2.3 m. The equipment is serviced by a tractor driver and 2 workers. The Productivity is 1600-3000 seedlings per hour. Productivity is affected by the quality of soil preparation and the complexity of the field. Both coniferous and deciduous seedlings can be planted[13].

In the thinning and main felling, various forest harvesters are used in woody shelter belts, which perform sawing, delimbing and bucking of individual trees for the preparation of timber. The design of woody shelter belts (relatively narrow woody bands and small tree dimensions) dictates the widespread use of compact class and small-class harvesters. One such small-class harvester is Nokka Profi (Keto 100 working head, Figure 10). Engine power 95 kW. Fuel consumption per working hour 11 L $^{h-1}$. Saw oil consumption 0.7 L h-^{1}. The mass of the harvester is 11.5 t, width is 2.5 m, the price of a harvester of this size is 250-350 thousand €; depreciation period – 4-5 years; depreciation of the working head – 2-3 years; maintenance and repair costs – 8.6 € h^{-1}; service cost (including oils and lubricants) 8.6 € h^{-1}. Administrative costs – 6

[12]https://egedal.dk/en/produkter/transplanter-type-k-0
[13]https:egedal.dk/en/produkter/transplanter-type-jt-0

thousand € per year; moving costs – 6 thousand € per year, insurance – 2 thousand € per year. In the calculations the machine's workload is 80% (2570 h per year). Productivity in the first thinning 5.6-10.3 m^3 h^{-1} (avg. trunk volume 0.05-0.1 m^3); productivity in the second thinning 9.1-12.7 m^3 h^{-1} (avg. trunk volume 0.1-0.15 m^3); in the regenerative felling this harvester is rarely used. The dimensions of the trees to be felled, the working head, the method of work, the qualification of the operator (Kärhä et al. 2004) are influenced by the property. Machines from this manufacturer are not available in Latvia.

Figure 10. Nokka Profi with Keto 100 working head.[14]

Another example of a small-class harvester, which is no longer in production at the moment, but is analogous to newer models, is the Timberjack 770 (working head of the Timberjack 742). Engine power 82 kW, fuel consumption 11 L h^{-1}, saw oil consumption 0.7 L h^{-1}. Empty mass 10.8 t, width 2.4 m, Harvester's utilization period – 4-5 years; depreciation of the working head – 2-3 years; maintenance and repair costs – 8.6 € h^{-1}; repair and service (including oil and lubricant costs) 8.6 € h^{-1}; administrative costs – t thousand € per year; moving costs – 6 thousand € per year, insurance – 2 thousand € per year. Average occupancy in studies 80% (2570 h per year). In Latvia, there are mostly the latest generation John Deere harvesters, which continue the development of Timberjack model lines; however, at the moment the company has completely abandoned production of light the 4-wheel harvesters.

[14]https://www.tori.fi/etela-pohjanmaa/Nokka_Profi_6_WD_90509141.htm

Figure 11. Timberjack 770 harvesters.

Another small-class harvester is the Sampo-Rosenlew 1046X (Keto 51 working head, Figure 12). The latest model in this series is the HR46. This harvester has 4 wheels, which improves maneuverability and reduces costs, but also increases the requirements for the bearing capacity of the bottom. Engine power 73.5 kW, fuel consumption 11 L h^{-1}, saw oil consumption 0.7 L h^{-1}, Empty mass 7 t, width 2.3 m. Depreciation period of the machine – 4-7 years; depreciation of the working head – 2-3 years; maintenance and other costs – similar to the above mentioned machines. Productivity indicators for this machine are not significantly different from other harvesters of similar size and power.

Figure 12. Sampo-Rosenlew 1046X harwester[15].

The larger mid-range four-wheeler is the ProSilva 810 (Keto 100 working head). Engine power 114 kW, mass 10 t, width 2.6 m, used machine price 168 thousand €. Depreciation period of the machine – 4-7 years; depreciation of the working head – 2-3 years. Productivity in the first thinning – average 7.6 m^3 h^{-1} (avg. trunk volume 0.11 m^3); in the second thinning – 10.4 m^3 h^{-1} (avg. trunk volume 0.18 m^3); in the regenerative

[15]https://www.mascus.lv/mezizstrade/lietoti-mezizstrades-harvesteri/sampo-rosenlew-1046x/ixmnlvfx.html

felling – 19.5 m^3 h^{-1} (avg. trunk volume 0.5 m^3). Yields are influenced by the type of felling, the number of sortage types to be prepared,the operator's qualifications and tree dimensions (Sirén & Aaltio 2003).

Figure 13. ProSilva 810 harvesters[16].

A very effective solution for sawing small-dimensional trees is the compact class harvester Vimek 404T6 (Keto Forst working head, Figure 14) with an engine power of 44 kW and fuel consumption of 4 L h^{-1}. Harvester's weight is 4.4 t, width 2.1 m, price – 180 thousand €; working head – 11 thousand €; depreciation period of the base machine, taking into account the relatively small load – 9 years; depreciation of the working head – 4 years; investment costs – 23 thousand € per year; staff costs – 56 thousand € per year; equipment maintenance costs – 34 thousand € per year; insurance – 3 thousand € per year. Productivity – avg. 5.3 m^3 h^{-1} (avg. trunk volume 0.05 m^3). Productivity is determined by the dimensions of the felled trees, the qualification of the operator, the type of felling and other factors (Lazdiņš et al. 2016).

[16]https://www.nettikone.com/prosilva/810/2107356

Figure 14. Vimek 404T6 harvester[17].

For continuous harvesting and shredding of bushy crops suitable agricultural tractor New Holland FR9090 with a working head of 130 FB (Figure 15), designed for sawing and chipping operations (harvesting the crop in front of the machine). Engine power 573 kW, fuel consumption 33 L h^{-1}. The empty mass of the base machine (agricultural tractor) is 13.1 t, width 3 m, length 8.5 m. The price of the base machine 350 thousand €; working head – 85-90 thousand €; depreciation period of the base machine – up to 12 years; depreciation period of the working head – up to 8 years (500 working hours per year); average sawing and chipping cost in 2012 were 213 € ha⁻¹ (1.8 € LV n^{-3}) excluding labor costs (Berhongaray et al. 2013).

Figure 15. New Holland FR9090 with 130 FB working head.[18]

Agricultural tract or John Deere 8520T with a Ny Vraa overgrowth harvester with a JF Z200-HYDRO/E or C2 working head (Figure 16) designed for cutting and chipping of the bushy crop. Engine power 227

[17]https://www.vimek.com/products/forestry-machines/404-se
[18]https://digitalcommons.esf.edu/hvstgal/13/

kW, fuel consumption 30 L h^{-1}. Empty mass of the base machine (agricultural tractor) 12.1 tons, width 2.6 m, length 5.2 m. The price of the base machine in 2013 was 125000 €; crop harvesting header – 46000 €; depreciation period of the base machine – up to 12 years; depreciation period of the harvester – up to 8 years (500 working hours per year); average cutting and shredding costs 84 € ha⁻¹, excluding labor costs (Berhongaray et al. 2013).

Figure 16. John Deere 8520T with JF Z200-HYDRO C2 working head.[19]

Harvesting of bushy cover can be done by mid-range harvester Valmet 901-4 with Naarva Grip 1600-40 working head (Figure 17), which acts like a guillotine and is significantly cheaper than a working head with a saw, but it also has less productivity and cannot cut down very small bushes (in willow plantings). Engine power 124 kW, fuel consumption 12 L h^{-1}, mass 14 t, width 2.7 m. The price of the base machine – 280 thousand €; working head – 17 thousand €; depreciation period of the base machine – 5 years; depreciation of the working head – 2-3 years; maintenance and repair costs – 6 € h^{-1}; administrative costs – 7 thousand € per year; the cost of moving machines – 6 thousand € per year, insurance – 2 thousand € per year. Productivity – average 3 m^3 h^{-1} (avg. trunk volume 0.007 m^3). Productivity is influenced by the thickness of plantations and the volume of trees cut down (Magagnotti et al. 2012).

[19]https://www.retrade.eu/en/aitem/448804/JF_Z200_Hydro_C_2-r%C3%A6kket_Pileh%C3%B8ster___Willow_harvester

Figure 17. Naarva Grip 1600-40 working head[20].

Compact-class forwarders, such as the Vimek 610, can be used to transport round timber and logging residues. Engine power 44 kW, fuel consumption 4 L h^{-1}. Empty mass 4.7 t, width 2.2 m. The price of the base machine – 130-150 thousand €; grapple – 3 thousand €; depreciation period of the base machine – 9 years; depreciation of the grapple – 5 years. Insurance costs – 3 thousand € per year. Productivity – 9.8 m^3 h^{-1} (forwarding distance – 250 m; average load – 5 m^3). Productivity is mainly influenced by the distance of the arrival and the driving conditions (Lazdiņš et al. 2016).

A mid-range forwarders such as the John Deere 810D provides lower delivery costs as the distance of increases. John Deere 810D engine power is 86 kW, fuel consumption 12 L h^{-1}, empty mass 9 t, width 2.7 m, forwarder price – 250 thousand €; depreciation period of the base machine – 7 years; insurance costs - 5 thousand € per year. Productivity – 10 m^3 h^{-1} (forwarding distance – 145 m; average load – 7.9 m^3). The service cost is influenced by the distance of the forwarding and the conditions in the stand, as well as the type of felling – selective or regenerative.

It is possible also use very small tractors, for example, Kranman Bison 10000 6WD, whose engine power is 18 kW, fuel consumption 2 L h^{-1}, empty mass 1.5 t, width 1.5 m, forwarder price in the maximum setup – 60 thousand €; depreciation period of the base machine – up to 9 years. Productivity – average 4.8 m^3 h^{-1} (arding distance – 300 m; average load – 2.2 m^3). The cost price is influenced by the conditions of forwarding and the distance (Kaleja et al. 2017).

To transport biomass to the roadside from the field farm tractors, for example, Valtra T161 with a trailer (capacity 22-30 m^3) can be used. Engine power 128 kW, fuel consumption10 L h^{-1}, empty mass 6 t, width 2.3 m, length, 5.1 m. Tractor price in 2021 was 120 thousand €; depreciation period – 10 years (1500 working hours per year). Fixed costs – 8.7 € h^{-1}; maintenance and repair costs – 1.9 € h^{-1}. Such a technique is usually serviced by 1 operator, but in case of heavy workload, you can also work in several shifts. Forwarding is carried out in winter, when in agriculture work does not take place. Average load – 7.8 t

[20]https://www.ebay-kleinanzeigen.de/s-anzeige/naarva-grip-1600-40-fallkopf/2088966808-276-6210

(naturally moist wood). At least 2 tractors are required to service one harvester if the chips had to be transported to the edge of the field and even more as the distance of access increases (Marchi et al. 2011).

For the renewal of woody shelter belts, stump extraction and tillage must be carried out. The stumps can then be used to prepare biofuel. Large forwarders can be used to transport stumps, since they are more suitable for transporting heterogeneous biomass, such as the Ponsse Bison S15 B1, for which more modern analogues are currently produced. Engine power 150 kW, fuel consumption 13 L h^{-1}, empty mass 13.8 t, width 2.8 m. Forwarder price in 2021 – 275 thousand €; depreciation period – 10 years. Productivity – average 7.8 m^3 h^{-1} (forwarding distance – 250 m; average load – 7 m^3; stock of stump material – 60 m^3 ha^{-1}). Productivity is influenced by the quality of stump harvesting and loading, operator experience, forwarding distance and terrain, as well as stump dimensions (Laitila et al. 2008).

Simultaneous chipping and delivery of the harvested material with a self-propelled chipper with crane and cargo tank can be done with a mid-range forwarder equipped with a chipper with a 350 kW autonomous engine and a chip carriage trailer (~20 m^3). Tractor engine power 140 kW, fuel consumption for chipping 3.2 L dry matter t^{-1} and 9-12 L h^{-1} for the forwarding. The cost of oils and lubricants accounts for 6% of the cost of fuel. Empty mass 17 t, width 2.8 m. The price of the base machine is 275 thousand €; chipper price – 625 thousand €; depreciation period of the forwarder – 10 years; chipper depreciation period – 12 years (1840 working hours per year for the forwarder and 1040 working hours per year for the chipper). The following equation can be used to estimate productivity:

$$T_{ch} * (\frac{T_{(tot.)}}{t_{dry}}) = \frac{0,85 + 0,016}{PS + \frac{13,2}{PS * P} + \frac{1132}{P}}$$

$where$:

T_{ch}– efficient chipping time;

$PS -$ average amount of chipped biomass, t_{dry};

P– nominal chapacity of the chipper engine, kW.

Forvarding distance – 80 m, speed of the forwarder 38 m $min.^{-1}$; unloading time of wood chips – 5 min. Yield is influenced by the type of chipper, forwarding distance, capacity of the chip trailer (Belbo & Talbot 2014).

Logging residues and small trees can also be chipped in a roadside with a diesel chipper, e.g. chipper with an independent engine Conehead V3000; Doppstadt DH 810; Jenz HEM 561 D; Morbark Hurricane XL 2400; Pezzolato PTH 900; Vermeer HG 40000. Engine power average 320 (± 91) kW, fuel consumption 2.2 (± 0.7) L t^{-1} (naturally moist wood). The price of a set of chipping equipment (chipper, loader and base machine) in 2018 was 300-500 thousand €. The intensity of use of machines varies significantly from one company to another, with data compiled in Italy that on average it is 700 h per year (up to 1200 h per year). Repair and maintenance costs – on average 20 thousand € per year; production costs – on average 13.5 € t^{-1} (naturally moist wood). Productivity on average – 19.1 t h^{-1} (naturally moist wood). Total annual production – on average 14700 t (naturally moist wood) per year. Productivity is determined by the type and power of the chipper (Spinelli et al. 2019).

An alternative solution is a chipper with a PTO drive, for example, Farmi 260 CH; Gandini TPS 35; Heizohack 8-400; Wust KPC12. The tractor's engine power averages 141, but for chipping larger dimensional trees, the engine power is up to 250 kW. Fuel consumption 3.3 L t^{-1} (naturally moist wood). The price of a set of chipping equipment (chipper, loader and base machine) 162-300 thousand €. The intensity of use of machines – on average 500 h per year; repair and maintenance costs – on average 10 thousand € per year; production cost – 26.5 € t^{-1} (naturally moist wood). Productivity averages 7.3 t h^{-1}; annual produced volume – 4800 t (naturally moist wood). Productivity is determined by the type and power of the chipper (Spinelli et al. 2019).

Chipping at the terminal or the end user side means that the small wood and the assortment of firewood are transported to the terminal and chipped there. This approach reduces transportation efficiency, as small trees and firewood have a lower load density and maximum possible load in comparison to wood chips, while an electric chipper can be used in a terminal, which allows you to significantly reduce the cost of chipping. However, in practice, the same chippers are often used as in a terminal as in roadside chipping. An example of such chipper is a mobile chipper with an engine power of 350 kW. Fuel consumption for chipping is 3.2 L of dry matter t^{-1}. The cost of oils and lubricants accounts for 6% of the cost of fuel. Empty mass 25 t. Chipper price – 400 thousand €; depreciation of the chipper – 12 years (1040 working hours per year).

Forwarding distance – 80 m, speed of the conveyor 38 m $min.^{-1}$; unloading time of wood chips – 5 min. (Belbo & Talbot 2014).

An alternative solution for chipping at a roadside is a mobile chipper mounted on a truck. An example is a mobile chipper with an engine power of 350 kW, fuel consumption 3.2 L of dry matter t^{-1}. The cost of oils and lubricants is 6% of the cost of fuel. Empty mass 28 t. The price of the chipper set is 450 thousand €; depreciation of the chipper – 12 years (Belbo & Talbot 2014).

Also, stumps can be used for the production of biofuel. The stumps are usually crushed at roadside with mobile crushers or carried to the terminal and crushed by stationary crushers. For example, the crushing machine GY-JP5000 can be used to crush the stumps[21]. Engine power – 283 kW, fuel consumption 30 L h^{-1}. Empty mass 15.6 t, width 9.7 m, length 3 m; height 3.6 m. Productivity 15-30 dry matter t h^{-1}. The more powerful unit GY-JP7000 have 313 kW engine, fuel consumption 35 L h^{-1}, mass 16.8 tons, width 3 m, length of 10.5 m and height of 3.6 m provides significantly higher productivity of 25-40 t h^{-1}.

Shredding of round timber at a terminal with an electrically operated chipper can be done with the Edsbyhuggen 250H crusher. Electric engine power – 30 kW, empty mass 0.9 t, productivity 10-15 m^3 h^{-1}. Yields are significantly affected by the average size of chipped trunks (Fulvio et al. 2015).

The delivery of roundwood is carried out by timber trucks, such as the SCANIA R580 with the ISTRAIL PL-03/35 trailer and forklift[22]. Engine power – 427 kW, fuel consumption 30 L per 100 km. Gross mass of the base machine 17.8 t, length 10 m, width 2.6 m, height 4.2 m; empty mass of trailer 5.7 t, length 13 m, width 2.6 m, height 4.4 m. The price of the base machine in 2007 – 232 thousand €. Such machines are usually serviced by 1-2 operators to ensure uninterrupted work. Productivity is affected by loading and unloading time, load size, timber transport distance (Laitila 2008).

An alternative solution is a timber truck with a trailer and forklift Volvo FH 540 with forklift Loglift 96 S. Engine power – 405 kW, fuel consumption 30 L per 100 km. Gross mass of the base machine 28 t, length 10 m, width 2.6 m, height 4.2 m; empty mass of trailer 5.7 t, length 13 m, width 2.6 m, height 4.4 m. The price of the base machine in 2008 – 232 thousand €. Productivity is determined by the time of loading and unloading, the load size, the distance of transportation (Laitila 2008).

[21]https://www.guoyumachinery.com/products/wood-processing/tree-stump-crusher.html

[22]https://www.mascus.lv/transports/lietots-kokvedejs/scania-r580-timber-truck-with-trailer/puf0nvhz.html

Delivery of chips to the place of consumption is carried out by means of a chip hauler. In Latvia, semi-trailers with a moving floor are most often used. The fuel consumption of the wood chip-carrying road train (tractor and semi-trailer)is 45 L per 100 km. Empty mass 17 t, load capacity 31 t (semi-trailer capacity 92 m³), total permissible mass of road train 48 t, total length of road train – 19.5 m. The price of the base machine in 2015 – 125 thousand €; depreciation period of the base machine – 10 years (378 thousand km); tire depreciation – 2 years or 120 thousand km); maintenance and repair costs – 16 thousand € per year; 2160 working hours per year. Insurance costs 6 thousand €. As a rule, chip haulers have 1 operator. Productivity – an average of 125000 LV m³ per year (average distance of the delivery in Finland 130 km one way, in Latvia – 68 km). Productivity is affected by loading and unloading time, load size, chip transport distance and waiting time for loading and unloading cargo (Laitila et al. 2016).

An alternative solution is a road train (truck and two containers), which is used in the Nordic countries, but which is not yet permissible in Latvia. Fuel consumption 55 L per 100 km. Empty mass 23 t, carrying capacity 37 t (semi-trailer capacity 129 m³), total permissible weight of road train 60 t, total length of automobile – 24 m. The price of the base machine is at least 144 thousand €; depreciation period of the base machine – 10 years. Productivity averages 126302 m³ per year (avg. distance of the route 130 km one way). Productivity is affected by loading and unloading time, load size, chip transport distance and waiting time for loading and unloading cargo (Laitila et al. 2016).

For the stump extraction in mature shelter belts for the restoration of plantations an excavator with a working head Väkev weighing 1.2 t and suitable for the extraction of stumps of various dimensions. For example, excavator Hitachi EX 225 USR. It's engine power is 122 kW, fuel consumption 15 L h^{-1}. Empty mass 24 t, width 2.8 m. Excavator price – 145 thousand €; the price of the working head – 15 thousand €; depreciation period of the base machine and the work head – 5 years; maintenance and repair costs – 5 € h^{-1}; administration costs – 4 thousand € per year, insurance – 1.6 thousand € per year at 50% occupancy (from 1500 h per year). Usually 1 operator. Productivity averages at 11.1 m³ h^{-1} or 4.8 t of dry matter (102 stumps h^{-1}, average stump diameter 30 cm). As the average stump diameter increases, productivity raises to 14.7 m³ h^{-1}, or 6.3 t of dry matter (74 stumps h^{-1}, average stump diameter 40 cm). Productivity is affected by the quantity of stumps and their dimensions (Kärhä 2012).

An alternative solution forstump digging is an excavator equipped with a working head Järvinen weighing 1.8 t. Such a working head can be effectively used excavator Hitachi EX 225 USR. Engine power 122 kW, fuel consumption 15 L $^{h-1}$. Excavator pashmass 24 t, width 2.8 m. Excavator price 145 thousand €; the price of the working head – 25 thousand €; depreciation period of the base machine and the work head – 5 years; maintenance and repair costs – 5 € $^{h-1}$; administration costs – 4 thousand € per year; insurance – 1.6 thousand € per year. Average occupancy in Finland 50% (from 1500 h per year). The machine is serviced in 1 opera. Productivity – an average of 10.2 m³ h-1 or 4.4 t of dry matter, or 99 strains $^{h-1}$ (average strain average 30 cm). As the strain average increases, the average yield increases by 13.3 m³ h-1, or 5.7 t of dry matter (67 strains $^{h-1}$, average strain average 40 cm). The machine is usually serviced by 1 operator. Productivity is affected by the state of forest reclamation, soil preparation in the forest, terrain, stump location and other factors (Kärhä 2012).

At different stages of production, front loaders are required. For this purpose, for example, the Liebherr 904 loader can be used. Engine power 95 kW, fuel consumption 33 L h^{-1}. Empty mass 20 t, width 2.6 m, length 9 m. Fork lifter price – 110 thousand €; depreciation period – 10 years (1500 work hours per year); fixed cost of the equipment – 12 € h^{-1}; maintenance and repair costs – 2,6 € h^{-1} at depreciation for 1500 working hours per year. The number of operators depends on the production process – from 1 to 3, if the equipment is needed around the clock. Productivity – 59 t of naturally moist material h^{-1}. The large mass and dimensions of forklifts are due to the need to carry the maximum load on each trip, as well as to raise the bucket over the board of the chip hauler (Marchi et al. 2011).

4 RECOMMENDATIONS FOR APPLICATION OF MECHANIZATION SOLUTIONS

The literature review based assessment of various technical solutions shows that a wide range of techniques should be involved in the establishment and management of woody shelter belts – from small-capacity agricultural tractors for soil preparation to powerful specialized equipment for biomass shredding. In most cases, one holding will only have at its disposal certain equipment necessary for the management of woody shelter belts, which, in addition, will be loaded with field work at the time when economic activity is also to be carried out on woody plants.

In view of these circumstances, it is recommended to outsource all stages of the establishment and management of woody shelter belts, providing, as far as possible, its services to an external service provider, such as soil preparation, grass sowing, early maintenance and grass harvesting. It is recommended to attract as few service providers as possible for the provision of services, so that at different stages of shelter belt management the mistakes made by the service providers do not become the responsibility of the land owner and do not increase the costs of managing woody shelter belts. The most important thing is to combine soil preparation, sown and planting services, or to carry out most of these works independently, inviting service providers to the planting company, independently providing planting material, the quality of which is critical.

5. PRODUCTIVITY OF HARVESTER PROTOTYPE ELABORATED IN LATVIA

In a collaboration between LSFRI Silava and SIA Laflora, a prototype of a new harvester for felling small trees and bushes has been developed. The prototype combine is intended for the production of biofuel or mulch (wood chips and eco-pellets of various lengths) in short rotation forests, protection belts around drainage ditches and overgrown agricultural land. The innovative element of the harvester is the use of gravity (bending of trees and shrubs by the tractor's own weight and formation of shoot clusters with header and base) for feeding circular saws and shredders, which significantly reduces the energy required to bend the shoots in the Chopper, which is the most energy intensive operation on other commercial pasture harvesters. Productivity studies were carried out in August 2022 in the Skriveri region in short rotation plantations established in 2011 within ERDF project No. 2010/0268/2DP/2.1.1.2.0/10/APIA/VIAA/118. In the study, willow trees of different ages (1, 3 and 5 years) were harvested. According to study results, the main factor affecting productivity in the study was coppice crop stock.

The driving speed of the base machine cannot be increased significantly to avoid clogging of the chipper feed and keep good quality of the wood chips; therefore, the reduction in the growing stock cannot be compensated for by driving faster in the field. It has also been found that when the stub diameter of an average shoot is less than 1 cm (20 cm and longer fragments from the chipper) and the saw blades are more often blocked by thin, flexible shoots, the chip quality deteriorates significantly. Likewise, clogging problems were found in a 5-year-old plantation. Optimum working conditions prevailed in three-year-old coppice forests; however, the driving speed of the base machine (MTZ 82 tractor) was still too high. The recommended speed in such conditions is 0.8-1.2 km/h. The yield achieved in the tests under these conditions in 3-year-old coppice was 2.4 tons of dry matter per hour. By increasing the power of the base machine (mainly to reduce ground speed while maintaining a minimum drive shaft power of 1000 rpm), productivity has been increased. There is still room for technical improvements to avoid clogging of the material in the chipper, blocking of the saw blades and improving the quality of the chips.

5.1.Materials and methods

Time studies aimed to demonstrate potential productivity in shelter belts planted with bushes were carried out at an agroforestry demo site located near Skrīveri, which was set up in 2011. The plantings were made according to a two-row planting scheme with a distance between the next rows of 75 cm and a distance between the seedlings in the rows of 50 cm. The distance between the centres of paired rows is 2.2 m. In practice, the distance between paired rows is often increased at the field ends, which may be related to peculiarities of planting technology. When the distance between paired rows is more than 80 cm, especially at the ends of the rows, hoeing with the new prototype harvester was difficult, both when forming a shoot bundle to be sawed and during sawing; Therefore, at the ends of such rows, only one of the paired rows could be cut at a time. This in turn increased the pressure on one side of the saw as one side of the saw was sawing and the stumps of the sawed wood after leaning backwards pressed on the saw wheel and periodically jammed the saw blade. The harvester was only effective in the willow plantation, where both rows could be cut simultaneously, using the front part of the saw blade, leaving the lowest stumps that did not press on the saw blades from below.

Productivity studies were performed in one-, three-, and five-year-old plantations where the average shoot lengths are 1.5 m, 3.2 m, and 6.3 m, respectively, the number of shoots in the undergrowth is 16, 8, and 4, and aboveground biomass 5 tons ha^{-1}, 16 tons ha^{-1} and 41 ton ha^{-1}. All trial plots were harvested at least once prior to the trial. The harvester prototype was mounted on an MTZ 82 tractor. The harvester consists of 3 elements: the header, which directs small trees into a more compact bundle in front of the machine, and the subframe, which attaches under the tractor, at the same time covering the less protected parts of the tractor, forming a bundle of shoots for cutting and chopping as well the sawing and chipping compartment with outlet behind the chipper (Figure 18).

The comminution device can be adapted to any tractor by adjusting the subframe and cutting unit accordingly. In the study, as part of the experiment, it was adapted to the MTZ 82 tractor.

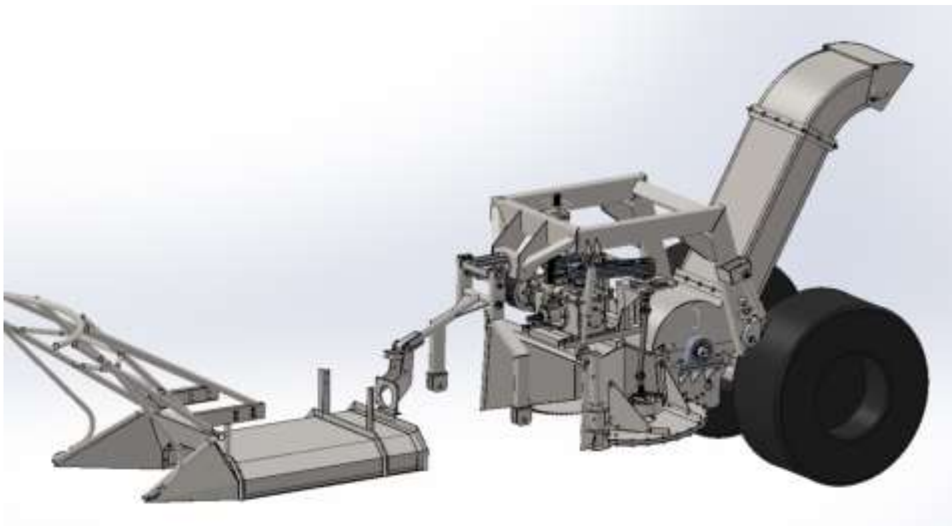

Figure 18. Harvester prototype.

The harvester is connected to the tractor via a PTO shaft, which transmits power to the saw blades and chopper via a transmission system. In the study, the PTO was set to 600 rpm (in reality up to 500 rpm) and additionally to 1000 rpm (in reality 800-900 rpm). With a speed of 600 rpm, the harvester was able to fell and shred small trees, but the chips were longer than 15-20 cm and had to be re-chaffed before use. Changing the PTO to 1000 rpm improved the quality of the wood chips, but the MTZ82 tractor used clearly lacked power in dense vegetation and the chipper occasionally got stuck. Another significant disadvantage of the MTZ 82 is its high driving speed, it could not go slower than 3 km h^{-1}, but the optimal driving speed when sawing is 0.8-1.2 km h^{-1}, so the tractor driver braked the tractor with the clutch, which is not recommended under the production conditions. To remedy this deficiency, another, more powerful tractor must be used. Another requirement for the tractor is to maintain a high PTO speed (minimum 1000 rpm) at low driving speeds.

The research involved implementing time studies using a handheld computer that was designed with shock and moisture-proof capabilities. The handheld device was also equipped with a specialized program that was specifically designed for accounting and recording working-time elements in units of centiminutes or cmin, which is equivalent to one minute. The process of harvesting is carried out within a single shift, specifically. The required duration of work is limited to a maximum of 4 to 6 hours, specifically during daylight hours. The time allocated to maintenance, cleaning, and adjustments of the chipper and saw will be deemed separate from the overall working time, given that such activities are closely linked to the technical readiness stage of the equipment. This approach ensures a more efficient utilization of working hours. Time study work elements are described in Table 1.

Table 1. Harvester time study elements

Working time category	No.	Explanation
Productive time	1.	Entry into field/row
	2.	Manoeuvring during work
	3.	Sawing and chipping
	4.	Interruptions to chip sawn material in dense vegetation
	5.	Departure from 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

5.2. Results of time studies

Statistical information related to the prevailing conditions during the productivity investigation, comprising of quantification and size determinants of biomass can be found in Table 2. Considerable attention has recently been given to the issue of climate change and its potentially devastating impacts on the environment. This phenomenon is caused by the excessive emission of greenhouse gases, primarily carbon dioxide, into the atmosphere as a result of human activities such as transportation, energy production, and industrial processes. The consequences of climate change include rising sea levels, extreme weather events, loss of biodiversity, and food shortages, among others. Therefore, it is imperative that we take immediate and effective measures to mitigate the effects of climate change and ensure the sustainability of our planet for future generations. In the present study, it was observed that the mean growing stock within the investigated regions ranged from 10 m^3 ha^{-1} in the case of one-year-old coppice, to as high as 91 m^3 ha^{-1} in the five-year-old plantation.

Table 2. Variables 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%
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

Pointer	Unit of measure	Annual shoots	Three-year shoots	Five-year shoots
	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

The summary regarding time studies and indicators of productivity, as displayed in the Table 3. The exclusion of long periods of interruption caused by equipment repairs from the designated work time is stipulated. Furthermore, once any deficiencies commonly associated with prototypes have been addressed in the harvester prototype and the optimum configurations for various nodes have been achieved, productivity shall remain unaffected. The average velocity of vehicular motion diminishes with the increase in biomass, and in a five-year plantation, it is expected to decline further under favourable circumstances. However, sustaining elevated Power Take-Off (PTO) velocity alongside this predicted phenomenon is not technically feasible.

Table 3. Assessment of harvesting 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
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 h^{-1}	2,3	6.2	13.4
	tons h^{-1}	1.0	2.8	6.1
Efficiency (actual work time)	-	85%	85%	85%
Adjusted yield	m^3 h^{-1}	1.9	5.3	11.4
	tons h^{-1}	0.9	2.4	5.1
Hourly cost of work	€ h^{-1}	48	48	48
The density of the pile of chips	LV m^3 ton^{-1}	5.2	5.2	5.2
Production costs	€ m^{-3}	24.8	9.1	4.2
	€ ton^{-1}	55.0	20.2	9.3

Pointer	Unit of measure	Annual shoots	Three-year shoots	Five-year shoots
	€ LV m^{-3}	10.6	3.9	1.8

The cultivation of a healthy growing stock is a crucial determinant of productivity and serves as a constraining factor for the utilization of the technique. The utilization of the harvester is considered optimal within the context of the three-year-old coppice, despite the requirement for a more potent tractor. The optimal design of a plantation is of considerable significance, with particular attention to the inter-row spacing in a double-row planting, which ought not to exceed a distance of 75 cm. Trimming the terminal shoots of crop rows using a brush cutter can potentially enhance access and manoeuvrability for agricultural machinery, thereby improving overall efficiency in field operations.

The majority of the labour hours are dedicated to sawing operations; however, as the coppice matures and expands in size, the time required for entering the rows and executing manoeuvrers increases, thereby leading to a heightened frequency of pause interruptions to release the saw blade or chipper.

The expense of chip manufacturing in relation to hourly equipment costs varies between 11 € LV m^{-3} in a one-year-old coppice and 2 € LV m^{-3} in a five-year-old coppice. A more accurate assessment of the prime cost may be obtained from a three-year-old plantation, at a rate of 4 € LV m^{-3}, due to the inadequacy of the equipment's capacity for prolonged operation in older coppices, at least in the current context.

The findings of the study substantiate that the harvester prototype effectively fulfils its designated tasks with regard to the harvesting of willow plantations, particularly when the willow shoots are not more than 3 years old, and have an average length of approximately 3 meters. When handling larger willows, it is imperative to undertake the expansion and reconstruction of both the header and subframe. The adequacy of saw and chipper throughput is contingent upon a consistently elevated rotational velocity of the PTO.

Experimental findings have indicated that the positioning of stems holds fundamental significance in the act of sawing, thereby rendering the machinery presently unsuitable for the uninterrupted severance and fragmentation of organic flora. One of the primary obstacles encountered in the use of saw blades is their potential to become obstructed by stump remnants from felled stems. This is particularly likely to occur when a saw is operated using the blade's edge, as opposed to the central portion of the blade. The aforementioned issue can be effectively resolved through the substitution of circular saws with chain saws. The aforementioned modality is applied in the Bracke C.16 harvesting mechanism's severing component. A potential alternative is the utilization of a free-hanging chain, as employed in the Bender harvester. Nonetheless, this proposed approach has yet to demonstrate practicality.

The MTZ 82 base machine, which was proposed for use in harvesting, has been found to be unsuitable due to its inherent limitations. Specifically, the optimal PTO rotation speed of the machine results in an excessively high driving speed which cannot be reduced. As a result, in order to accommodate the requirements of production harvester prototypes, it is recommended that more powerful machinery be utilized. Specifically, tractors with the lowest feasible movement speed at the optimal PTO rotation speed should be selected. In order to achieve wood chips of superior quality, it is imperative that the PTO maintain a minimum speed of 1000 RPM. By decreasing the rotational velocity, the size of the chips is prolonged, and at a speed of 500 revolutions per minute, chips are no longer produced, but rather partially mangled fragments are extracted from the chipper. The potential for modifying the length of chips through manipulation of the rotational velocity of the chipper or the protrusion of knife blades is constrained due to the significant obstruction caused by the protrusion of knife blades on the feeding of shoots into the chipper, as well as the emergence of obstructions both above and below the saws during the chipping process. A viable option is to engage in a transmission reconstruction process by altering the dimensions of the gears that are connected to the saws and chippers. However, it is worth noting that this particular approach has yet to be subjected to empirical experimentation.

The replacement of circular saws with chain saws is considered to be the foremost prospective enhancement of the harvester. The aforementioned enhancement of the harvester's utility to encompass harvesting in natural vegetation is accompanied by a concomitant escalation in both initial and ongoing maintenance outlays, consequently doubling the cost of acquisition and maintenance. During the trials, certain improvements were partially implemented, including an increase in the thickness of the counter-knife plate to diminish the protrusion of the chipper knives and mitigate the risk of the counter-knife bending. Furthermore, the header can now be lowered to cover broader coppices, primarily at the terminations of the rows. An alternative approach would involve augmenting the width of the header; however, this modification could potentially impede the traversal of equipment upon roadways and diminish performance in areas with shrubbery of low height. In order to ensure unrestricted equipment manoeuvring, adaptation of the subframe to the base machine is imperative. Enhancement of the mounting points of the chipper rotor is recommended, with a view to augmenting its resistance when subjected to higher loads.

The current research sought to examine a hypothesis positing that the incorporation of a sub-frame during the bundle formation process of wood harvesting, in conjunction with an augmented feeding system for the chipper, would result in a corresponding reduction in the power requirements of the machinery utilized for coppice harvesting. The results of the study have verified this hypothesis. The substitution of the technique for managing "bending in" shoots with a tilting method results in a significant decrease in the power demand of the recommended equipment for coppice cutting by a magnitude of up to threefold. Furthermore, the MTZ 82 implement can effectively perform the harvesting of shoots up to three years old.

The procurement of coppice necessitates the utilization of tractors capable of driving at reduced velocities, reaching a minimum speed of 0.5 km per hour, while simultaneously maintaining a power take-off (PTO) rate of no less than 1000 revolutions per minute. The harvesting process of bush lands that have developed naturally necessitates substantial enhancements, such as the replacement of the sawing apparatus with a chain saw to prevent the obstruction of the cutting compartment.

Upon the resolution of insignificant technical difficulties uncovered during the research, it is advised that the devised resolution be implemented in young willow and poplar SRC, particularly in the context of single-row plantations. However, it is imperative to employ a more robust base machine to ensure optimal outcomes.

The harvester prototype is suitable for shelter belts and in theory it results in the lowest costs in comparison to available solutions; however, it has not reached maturity stage and further development is needed to use this technology in the industrial scale.

6. GREENHOUSE GAS ASSESSMENT IN HARVESTING OPERATIONS

The National energy and climate plan for Latvia in 2021-2030 has identified biomass as a critical constituent of the prospective renewable energy repertoire for the country. The plan has underscored the importance of forest resources, which make a substantial contribution to the total indigenous biomass supply (Ministru kabinets 2020). The forest resources encompass the remnants originating from the harvesting activities conducted in the commercial forests and from the sawmills. The present harvest rate has the potential to generate a maximum of 128411 TJ of primary energy, according to source (Līcīte et al. 2021). Residues are comprised of diminutive and flawed pieces of timber in circular form, branches, apexes of stems, small trees of understory, and stumps. Meanwhile, sawmills generate sawdust and slab wood. It is foreseen that the industries that utilize timber will exploit the conveniently accessible resources, including small roundwood and sawdust, while the residual amount will be made available to novel energy projects that are based on biomass. A notable proportion of the residual biomass is typically left in forested areas during the process of felling operations as a result of the ample availability of alternative resources. The utilization of logging byproducts, namely sawmill residues and firewood, has been documented (Björheden 2006). The present circumstance is undergoing significant change owing to Russia's aggression in Ukraine. As a direct consequence, forest biofuel prices escalated thrice over the course of 2022 as a result of the cessation of biomass importation from both Russia and Belarus (Zalāne 2022). Currently, the production of various forms of forest biofuels is becoming increasingly feasible. In addition, there is a growing recognition of the importance of considering environmental factors in biofuel production processes. This includes the need for adherence to sustainability criteria as mandated by regulations such as 2018/2001 (European Commission 2018).

One of the sustainability criteria that warrants attention pertains to the greenhouse gas (GHG) emissions resulted from the production and delivery of biofuels. The delivery of solid biofuel is subject to regulation, whereby emission factors are provided for delivery distances beginning at 500 kilometres. However, it is noteworthy that delivery distances of forest biofuel in Latvia are markedly shorter (Līcīte et al. 2021).

The assessment of the impact of climate change resulting from the production and delivery of forest biofuel is a multifaceted procedure that necessitates several activity data and assumptions. This process is distinguished by its intricacy in calculations, which stems from the requirement to ensure a harmonious correlation between productivity and materials' consumption throughout the various stages of forest biofuel production. This study seeks to provide estimates of greenhouse gas (GHG) emissions resulting from forest biofuel production and delivery in Latvia to use these data later in the decision support tools. To achieve this objective, the study employs actual productivity figures collected from the Joint stock company "Latvia's state forests" (JSC), as well as data derived from literature reviews and information provided by forestry companies and farmers on fuel consumption, and consumption of materials such as oil, grease, and refrigerants. This study examines the predominant forest biofuel supply chains, encompassing the transportation of harvesting residues from regenerative cuttings, full tree harvesting on neglected agricultural lands and forest drainage trenches, as well as from pre-commercial thinning. The evaluation process employs the customary arrangement of forest machinery, encompassing harvesters, forwarders, chippers and chip trucks. This research endeavour pertains to a more extensive evaluation of greenhouse gas (GHG) emissions within the context of forestry operations.

6.1. Materials and methods

The foundational premises involved in the computation encompass the rate of fuel and lubricant consumption per unit of working hour alongside productivity; this necessitates amalgamating diverse task components and environmental circumstances, such as. The parameter of transportation pertaining to the spatial extent between two points, commonly referred to as the delivery distance, is a fundamental element in logistics and supply chain management. A questionnaire was developed for the purpose of collecting the essential data outlined in Table 4. The partner organizations partially provided the production statistics collected by the companies. Scientific literature yielded for incomplete data.

Table 4. Evaluated productivity and GHG source indicators

Group	No.	Title	Comment
Fuel and electricity consumption	1.	average L per engine hour	fuel consumption during operation or average fuel consumption if more precise data is not available
	2.	L 100 km^{-1} (outside the city with and without load)	average fuel consumption
	3.	L 100 km^{-1} (in city with and without load)	average fuel consumption, in addition, the the proportion of the distance travelled in the city is used
	4.	regardless of the type of felling, L LV m^{-3}	average fuel consumption (chipper, loader) per loose volume (LV) of forest biofuel
	5.	regardless of the type of felling, kWh LV m^{-3}	electricity consumption (chipper)
Consumption of lubricants and oil, filling of conditioners	6.	lubricants, transmission and hydraulic oil, g per engine hour	the average consumption of lubricants for the lubrication of the manipulator and other moving parts excluding bio-oils
	7.	motor oil, g per hour / km^{-1}	the average engine oil consumption during regular maintenance is converted to engine hours; for a chainsaw – oil that is mixed with fuel
	8.	air conditioner agent, g per engine hour	average consumption during breakdowns and regular maintenance
	9.	chain oil, g m^{-3} / m^{-3}	the consumption of chain oil for the production of logs and firewood, excluding bio-oils
Seasonality	10.	monthly distribution of work time	percentage distribution of load when producing forest biofuel, LV m^3, working hours or km per month
Relocation of equipment and transport distances	11.	distance of relocation of equipment, km	the average distance of moving machinery with a trailer in one direction depending from machine and felling type
	12.	forwarding distance, m	average off-road transport distance depending from felling and machine type
	13.	moving equipment (times per year)	number of trips per year related to the relocation of equipment
	14.	chip transport distance, km	chip delivery distance in one direction
	15.	firewood transportation distance, km	firewood delivery distance in one direction
	16.	chip truck loading time, min.	loading and unloading time
Productivity	17.	logging residues, LV m^3 h^{-1}	average productivity, harvesters and chainsaws (only if the production of logging residues increases fuel consumption)
	18.	firewood, m^3 h^{-1}	average productivity depending from felling type
	19.	wood chips, LV m^3 h^{-1}	average productivity for chipping and chip handling

Group	No.	Title	Comment
	20.	whole tree harvesting, LV $m^3\ h^{-1}$	average productivity depending from felling type
Load size	21.	off-road transport of harvesting residues and whole trees, LV m^3	average load size depending from felling type
	22.	off-road transport of roundwood logs, m^3	average load size depending from felling type
	23.	chip truck, LV m^3	average load size
	24.	log truck, m^3	average load size

The fuel emission factors utilized were sourced from the guidelines established by the Intergovernmental Panel on Climate Change (IPCC), whereby the road and off-road transportation sectors were distinguished. The emission factors pertaining to diesel and various oils have been sourced from Latvia's national Greenhouse Gas (GHG) inventory report (Ministry of Environmental Protection and Regional Development 2022). A tabular representation of the values utilized in the ensuing computations can be found in Table 5.

Table 5. Characteristics and emission factors of fuels and lubricants

Fuel	The net heat value		Density, kg L^{-1}	CO_2, tons t^{-1}	CO_2, tons TJ^{-1}	CH_4, kg TJ^{-1}	N_2O, kg TJ^{-1}
	MJ L^{-1}	MJ kg^{-1}					
Diesel fuel in off-road transport	36.0	42.6	0.8	-	74.7	5.5	28.0
Diesel fuel in road transport	36.0	42.6	0.8	-	74.8	2.8	2.8
Lubricants	-	41.9	-	0.6	-	-	-
Transmission and hydraulic oil	-	39.5	1.0	0.6	-	-	-
Engine and chain oil	39.2	39.5	1.0	0.6	-	-	-

The remaining assumptions have been succinctly collated in Table 6. It is postulated that during the months of summer, the ratio of bio-additive is approximately 6%. This indicator has the potential to be expanded in order to calculate the magnitude of the effects resulting from the partial or complete replacement of fossil fuels with biofuels on greenhouse gas emissions. The determination of the density of wood chips and the calorific value of wood chips and firewood have been sourced from regulatory guidelines set forth in Cabinet of Ministers No. 42. According to Ministru Kabinets (2018) the aforementioned topic has been discussed in various academic circles. The mean relative density of wood, carbon content within wood, and the global warming potentials of methane (CH_4) and nitrous oxide (N_2O) were derived from the national greenhouse gas (GHG) inventory report of Latvia for the year 2022. This report aligns with the IPCC Fourth Assessment Report (Ministry of Environmental Protection and Regional Development 2022).

Table 6. Coefficients and conversion factors

No.	Indicator and unit of measure	Numerical value
1.	The proportion of bio-additives in fuel in the summer months	6%
2.	The lowest calorific value of chips (GJ LV m^{-3})	3.3
3.	The net calorific value of firewood at 40% relative humidity (GJ LV m^{-3})	10.0
4.	Average wood density (tonnes m^{-3})	0.42

No.	Indicator and unit of measure	Numerical value
5.	Average carbon content in biomass	50%
6.	CH_4 global warming potential	25.0
7.	N_2O global warming potential	298.0
8.	HFC134-A (refrigeration agent) GHG equivalent	1430.0

In order to properly assess the consumption of fuel, lubricants, and other necessary materials during forest operations, the utilization of average productivity estimates provided by the partner organizations, in conjunction with a cost calculation tool developed by Ackerman et al. (2014), is crucial. In the year of 2014, the aforementioned method was utilized. The biofuel supply chains related to forest management have been assessed. These include (1) the extraction of harvesting residues during regenerative felling using a mid-class forwarder, (2) the harvesting of woody vegetation in abandoned farmlands with a compact-class harvester and forwarder, (3) the extraction of woody vegetation from ditch-sides with the use of a mid-class harvester and forwarder, (4) the extraction of undergrowth trees during pre-commercial thinning (with an average tree height of 9-12 m) with a compact-class harvester and forwarder, along with firewood production from (5) regenerative felling and (6) thinning performed by large and mid-class harvesters and forwarders, respectively. The supply chains in question are responsible for over 90% of forest biofuel deliveries in Latvia including biofuel deliveries from drainage ditch cleaning operations. With the exception of the production of firewood, it is postulated that the act of hipping is executed at a location near a thoroughfare, followed by the utilization of road transport for a span of 70 kilometers. This process is accomplished through the deployment of two container chip trucks, each possessing a capacity of 70 cubic meters. The average distance covered during transportation is 68 kilometers, whereas the average forwarding distance recorded stands at 480 meters. The process of chipping is typically conducted at the roadside. The study employed research data to obtain the necessary information concerning the equipment utilized, as presented in the subsequent summary:

- compact class harvester (Ligné et al. 2005; Zimelis et al. 2017a; b, 2020), mid-class harvester (Miyata 1980; di Fulvio et al. 2012; Zimelis & Spalva 2022) and large harvester (Miyata 1980; Bergström & Fulvio 2014; Kizha & Han 2016; Björheden 2017);
- compact class forwarder (Forest Research An agency of the Forestry Commission 2000; Lazdiņš et al. 2016; Petaja et al. 2017b), middle class forwarder (Thor et al. 2006; Lazdiņš & Thor 2009; Lazdiņš & Gercāns 2011; Eriksson & Lindroos 2014; Petaja et al. 2017a) and large forwarder (Miyata 1980; Bergström 2019; Ferreira et al. 2019);
- self-propelled chipper relocated by tractor (Hakkila 1989; Kuhmaier 2011);
- trailer for relocation of forwarders and harvesters (Kalēja et al. 2017; Fernandez-Lacruz et al. 2020; Schnorf et al. 2021);
- timber truck (Thor et al. 2006; Kalēja et al. 2014) and chip truck with two containers (Thor et al. 2006; Lazdiņš & Thor 2009; Kalēja et al. 2017).

Greenhouse gas emissions generated in the production process are determined by assessing the emissions associated with each unit of production, the quantity of carbon dioxide emitted per ton of forest-based biofuel, and the net heat value of the fuel derived from forest sources. The identical presumptions are employed in both the processes of chipping and biomass delivery.

6.2. Results

The carbon footprint resulting from the transportation, processing, and distribution of forest harvesting residues obtained from regenerative felling over a distance of 70 km amounts to 1.4 kg of carbon dioxide equivalent. Table 7 presents the findings relevant to GJ^{-1}. Increasing the transportation distance to 150 kilometers would result in a rise in the overall greenhouse gas (GHG) emissions, which would ascend to 1.7 kilograms of carbon dioxide equivalent per gigajoule (kg CO_2 eq GJ^{-1}).

Table 7. GHG emissions due to production and delivery of biofuel from logging residues in clearfelling

Equipment	kg CO_2 eq LV m^{-3}	kg CO_2 eq ton^{-1} CO_2	kg CO_2 eq GJ^{-1}
Mid-class forvarder	1.5	4.9	0.4
Chipper	1.6	5.1	0.5
Chip truck	1.6	5.1	0.5
Total	4.7	15.2	1.4

The quantification of greenhouse gas (GHG) emissions caused by the transportation of woody biofuel from abandoned agricultural plots is determined based on the productivity of Vimek forwarder and harvester equipment, utilizing data from a related research investigation. Under optimal production conditions, the productivity is anticipated to increase, since the study examined the boundaries of mechanization. According to Table 5, the supply chain incurs a greenhouse gas (GHG) emission of 1.9 kilograms of carbon dioxide equivalent per gigajoule (CO_2 eq GJ^{-1}) as a result of the delivery of biofuel.

Table 8. GHG emissions due production and delivery of biofuels from overgrown farmlands

Equipment	kg CO_2 eq LV m^{-3}	kg CO_2 eq ton^{-1} CO_2	kg CO_2 eq GJ^{-1}
Compact class harvester	1.4	4.5	0.4
Compact class forvarder	1.5	4.9	0.5
Chipper and chip truck	3.2	10.2	1.0
Total	6.1	19.7	1.9

The estimation of greenhouse gas (GHG) emissions resulting from the removal of biomass from ditches, which can be identified also as harvesting of trees in shelter belts, is ascertained by applying research findings. As a salient consideration, the examined threshold values of productivity were assessed under particularly rigorous circumstances. Consequently, it may be postulated that the actual productivity levels achieved in operational settings would be higher. The aggregate greenhouse gas (GHG) emissions incurred in the manufacture and transportation of wood chips amount to 2.1 kg CO_2 equivalent per gigajoule, as presented in Table 9.

Table 9. GHG emissions due to biofuel extraction in ditch cleaning operations

Equipment	kg CO_2 eq LV m^{-3}	kg CO_2 eq ton^{-1} CO_2	kg CO_2 eq GJ^{-1}
Mid-class harvester	1.7	5.7	0.6
Mid-class forvarder	0.6	2.1	0.5
Chipper and chip truck	3.2	10.2	1.0
Total	5.5	18.0	2.1

Early thinning is another alternative, which can be compared with management operations in shelter belts, while thinning secong generation too dense stands. Average GHG outputs due to woody biofuel production in early thinning is 2.2 kg CO_2 eq GJ^{-1} (Table 10).

Table 10. GHG emissions due to production and delivery of forest bofuel from pre-commercial thinning

Equipment	kg CO_2 eq LV m^{-3}	kg CO_2 eq ton^{-1} CO_2	kg CO_2 eq GJ^{-1}
Compact class harvester	2.3	7.5	0.7
Compact class forvarder	1.5	4.9	0.5
Chipper and chip truck	3.2	10.2	1.0
Total	7.0	22.7	2.2

The production of firewood as the principal biofuel source in state-owned forests holds a significant degree of prevalence. The mean greenhouse gas (GHG) discharges attributable to the production of firewood via clearfelling are estimated to be 0.6 kilograms of carbon dioxide (CO_2) equivalent per gigajoule (GJ), as outlined in Table 11. Commercial thinning activities have been found to result in an elevation of greenhouse gas (GHG) emissions up to 1.0 kg CO_2 equivalent per gigajoule (GJ), attributable to notably larger emissions arising from forwarding processes where mid-class forwarders are utilized.

Table 11. GHG emissions due to production and delivery of firewood from clear-felling

Equipment	kg CO_2 eq m^{-3}	kg CO_2 eq ton^{-1} CO_2	kg CO_2 eq GJ^{-1}
Large harvester	1.6	2.1	0.2
Large forwarder	1.5	1.9	0.1
Log truck	3.4	4.4	0.3
Total	6.5	8.4	0.6

The European Union (EU) regulation 2018/2001 stipulates established values for specific classifications of forest biofuels, which include harvesting residues (1.6 g CO_2 eq MJ^{-1} for the production phase and 3.0 g CO_2 eq MJ^{-1} for the delivery phase), as well as roundwood biomass (0.3 g CO_2 eq MJ^{-1} for the production phase and 3.0 g CO_2 eq MJ^{-1} for the delivery phase) (European Commission 2018). The present study elucidates that greenhouse gas emissions resulting from the extraction of harvesting residues exhibit a significant reduction when compared to standard values outlined in regulations. Conversely, greenhouse gas emissions related to firewood production remain similar to default values, but delivery-related emissions can be up to 9 times smaller based upon the findings presented therein. This phenomenon is, to some extent, linked to varying delivery distances wherein the regulation stipulates a starting point of 500 km, while in the locality under study, the typical distance is approximately 68 km. A recent investigation conducted in Finland (Kärhä et al. 2022) has revealed that the production of roundwood results in comparable levels of greenhouse gas (GHG) emissions, namely 3.6 kg CO_2 eq m^{-3}, and our own research has found 3.1 kg CO_2 eq m^{-3} during clear felling activities. Similarly, thinning activities were found to contribute 6.2 kg CO_2 eq m^{-3} in the aforementioned study, and our investigation yielded a slightly higher value of 6.8 kg CO_2 eq m^{-3}.

It is also concluded in the study that despite the plethora of literature on harvesting productivity, there remain notable lacunae in the data pertinent to the computation of GHG emissions. Consequently, the assessment of GHG emissions in our study is predominantly informed by research data, which may not accurately represent typical production scenarios. The industrial sector is tasked with acquiring and organizing data pertaining to the utilization of resources during the production and distribution of forest-derived biofuel.

The estimated emissions are considerably lower than the standard values prescribed in Regulation (EU) 2018/2001, thereby complying with other corresponding research outcomes. The observed dissimilarities between the default values specified in Regulation (EU) 2018/2001 and the research-derived data primarily pertained to the biofuel delivery process. Consequently, further elucidation of this process is required to provide comprehensive justification for the notably diminished emissions.

It is necessary to ascertain the threshold levels of productivity and resource consumption in order to elucidate the causes of unfavorable outcomes and evaluate the potential for improvement. This knowledge will enable us to effectively mitigate greenhouse gas emissions, as evidenced by successful cases. The present study additionally corroborates that utilizing the research findings as a surrogate for factual production data may result in either an overestimation or an underestimation of emissions due to the likelihood of the research not being representative of typical production circumstances.

LITERATURE USED

1 Ackerman, P., Belbo, H., Eliasson, L., de Jong, A., Lazdins, A. & Lyons, J. (2014). The COST model for calculation of forest operations costs. *International Journal of Forest Engineering*, 25 (1), 75–81. https://doi.org/10.1080/14942119.2014.903711

2 Belbo, H. & Talbot, B. (2014). Systems Analysis of Ten Supply Chains for Whole Tree Chips. *Forests*, 5 (9), 2084–2105. https://doi.org/10.3390/f5092084

3 Bergström, D. (2019). Cost Analysis of Innovative Biomass Harvesting Systems for Young Dense Thinnings. *Croatian journal of forest engineering*, 40 (2), 221–230. https://doi.org/10/gf7s37

4 Bergström, D. & Fulvio, F.D. (2014). Comparison of the cost and energy efficiencies of present and future biomass supply systems for young dense forests. *Scandinavian Journal of Forest Research*, 29 (8), 793–812. https://doi.org/10/f3p67t

5 Berhongaray, G., El Kasmioui, O. & Ceulemans, R. (2013). Comparative analysis of harvesting machines on an operational high-density short rotation woody crop (SRWC) culture: One-process versus two-process harvest operation. *Biomass and Bioenergy*, 58, 333–342. https://doi.org/10.1016/j.biombioe.2013.07.003

6 Björheden, R. (2006). Drivers behind the development of forest energy in Sweden. *Biomass and Bioenergy*, 30 (4), 289–295. https://doi.org/10/cd4sc2

7 Björheden, R. (2017). Development of bioenergy from forest biomass - a case study of Sweden and Finland. *Croatian Journal of Forest Engineering : Journal for Theory and Application of Forestry Engineering*, 38 (2), 259–268

8 Ehlert, D. & Pecenka, R. (2013). Harvesters for short rotation coppice: current status and new solutions. *International Journal of Forest Engineering*, 24 (3), 170–182. https://doi.org/10.1080/14942119.2013.852390

9 Eriksson, M. & Lindroos, O. (2014). Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. *International Journal of Forest Engineering*, 25 (3), 179–200. https://doi.org/10.1080/14942119.2014.974309

10 European Commission (2018). *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance.)*. *OJ L*. http://data.europa.eu/eli/dir/2018/2001/oj/eng [2023-02-20]

11 F. Lavoie, P. Savoie, L. D’Amours, & H. Joannis (2008). Development and Field Performance of a Willow Cutter-Shredder-Baler. *Applied Engineering in Agriculture*, 24 (2), 165–172. https://doi.org/10/gdxs94

12 Fernandez-Lacruz, R., Eriksson, A. & Bergström, D. (2020). Simulation-Based Cost Analysis of Industrial Supply of Chips from Logging Residues and Small-Diameter Trees. *Forests*, 11 (1), 1. https://doi.org/10.3390/f11010001

13 Ferreira, F. de A.C., Freitas, L.C. de, Leite, E. da S. & Barros, A.P. da S. (2019). Geotechnology as a Planning Tool in the Determination of Forest Extraction Costs. *Floresta e Ambiente*, 26 (4), e20170879. https://doi.org/10.1590/2179-8087.087917

14 Forest Research An agency of the Forestry Commission (2000). *The Vimek 606D mini-forwarder*. (1400A/12/00 7.12a). https://www.forestry.gov.uk/pdf/ODW712a.pdf/$FILE/ODW712a.pdf

15 di Fulvio, F., Bergström, D., Kons, K. & Nordfjell, T. (2012). Productivity and Profitability of Forest Machines in the Harvesting of Normal and Overgrown Willow Plantations. *Croat. j. for. eng.*, 33 (1), 25–37

16 Fulvio, F.D., DiEriksson, G. & Bergström, D. (2015). Effects of Wood Properties and Chipping Length on the Operational Efficiency of a 30 kW Electric Disc Chipper. *Croatian Journal of Forest Engineering*, 36 (1), 85–100

17 Hakkila, D.P. (1989). Comminution of Residual Forest Biomass. In: *Utilization of Residual Forest Biomass*. Springer Berlin Heidelberg. 261–304. http://link.springer.com/chapter/10.1007/978-3-642-74072-5_5 [2015-08-05]

18 Kalēja, S., Brencis, M. & Lazdiņš, A. (2014). *Apaļo kokmateriālu un šķeldu piegādes ražīguma salīdzinājums jaunaudžu kopšanā (comparison of productivity of delivery of roundwood and chips in pre-commercial thinning)*. (Atjaunojamo energoresursu produktu ražošanas, pārstrādes un loģistikas rūpnieciskais pētījums, 2014/02). Salaspils: LVMI Silava.

19 Kalēja, S., Lazdiņš, A., Zimelis, A. & Spalva, G. (2017). Model for cost calculation and sensitivity analysis of forest operations. *Agronomy Research*, 16 (5), 2068–2078. https://doi.org/10.15159/AR.18.207

20 Kaleja, S., Zimelis, A., Lazdins, A. & Johansson, P.O. (2017). Comparison of productivity of Kranman Bison 10000 forwarder in stands harvested with harvester and chainsaw. *Proceedings of the 8th International Scientific Conference Rural Development 2017*, (In press). https://doi.org/10.15544/RD.2017.199

21 Kärhä, K. (2012). Comparison of two stump-lifting heads in final felling Norway spruce stand. *Silva Fennica*, 46 (4), 625–640

22 Kärhä, K., Haavikko, H., Kääriäinen, H., Palander, T., Eliasson, L. & Roininen, K. (2022). *Fossil-fuel consumption and CO2eq emissions of cut-to-length industrial roundwood logging operations in Finland*. In Review. https://doi.org/10.21203/rs.3.rs-2063961/v1

23 Kärhä, K., Rönkkö, E. & Gumse, S.-I. (2004). Productivity and Cutting Costs of Thinning Harvesters. *International Journal of Forest Engineering*, 15 (2), 43–56. https://doi.org/10.1080/14942119.2004.10702496

24 Kizha, A.R. & Han, H.-S. (2016). Processing and sorting forest residues: Cost, productivity and managerial impacts. *Biomass and Bioenergy*, 93, 97–106. https://doi.org/10.1016/j.biombioe.2016.06.021

25 Kofman, P.D. & Spinelli, R. (1997). *An Evaluation of harvesting Machinary for Short Rotation Coppice Willow in Denmark*. (87-986376-1–4). ELSAMPROJEKT. https://www.osti.gov/etdeweb/servlets/purl/598289

26 Kuhmaier, M. (2011). *Estimation of emissions during chipping operations & evaluating innovative supply chains in orchards*. (18). Vienna, Austria. http://www.forestenergy.org/filedata/1348825268study_report_18_kuehmaier_28.pdf?PHPSESSID=4b2d6ed178f00294f48d8f4ffb87e42c

27 Laine, T. & Saarinen, V.-M. (2014). Comparative study of the Risutec Automatic Plant Container (APC) and Bracke planting devices. *Silva Fennica*, 48 (3). https://doi.org/10.14214/sf.1161

28 Laitila, J. (2008). Harvesting technology and the cost of fuel chips from early thinnings. *Silva Fennica*,. https://doi.org/10.14214/sf.256

29 Laitila, J., Asikainen, A. & Ranta, T. (2016). Cost analysis of transporting forest chips and forest industry by-products with large truck-trailers in Finland. *Biomass and Bioenergy*, 90, 252–261. https://doi.org/10.1016/j.biombioe.2016.04.011

30 Laitila, J., Ranta, T. & Asikainen, A. (2008). Productivity of Stump Harvesting for Fuel. *International Journal of Forest Engineering*, 19 (37–47)

31 Lazdina, D., Lazdinš, A., Karinš, Z. & Kāposts, V. (2007). Effect of sewage sludge fertilization in short-rotation willow plantations. *Journal of Environmental Engineering and Landscape Management*, 15 (2), 105

32 Lazdiņa, D., Lazdiņš, A., Kariņš, Z. & Komorovska, A. (2007). Waste water sewage sludge usage as fertilizer of short rotation forest plantations. *Proceedings of The Third International Scientific Conference Rural Development 2007*, Kaunas, Lithuania, 2007. 287–293. Kaunas, Lithuania: Akademija

33 Lazdiņš, A. & Gercāns, J. (2011). *Productivity of forwarding depending from driving conditions*. Tampere, Finland, Helsinki University Hyytiälä Forestry Field Station.

34 Lazdiņš, A., Prindulis, U., Kalēja, S., Daugaviete, M. & Zimelis, A. (2016). Productivity of Vimek 404 T5 harvester and Vimek 610 forwarder in early thinning. *Agronomy Research*, 14 (2), 475–484

35 Lazdiņš, A. & Thor, M. (2009). Bioenergy from pre-commercial thinning, forest infrastructure and undergrowth – resources, productivity and costs. *Proceedings of Research for Rural Development 2009*, Jelgava, 2009. 147–154. Jelgava: Latvia University of Agriculture

36 Līcīte, I., Makovskis, K., Kalēja, S., Zimelis, A., Champion, J. & Lazdiņš, A. (2021). Greenhouse gas mitigation potential of forest biofuel originated in Latvia. *Rural Development*, 106–111. https://doi.org/10.15544/RD.2021.018

37 Liepins, Lazdina, D. & Lazdins, A. (2011). Productivity and Cost-effectiveness of the M-Planter Tree Planting Machine in Latvian Conditions. *Baltic Forestry*, 17 (2(33)), 308–313

38 Ligné, D., Nordfjell, T. & Karlsson, A. (2005). New Techniques For Pre-Commercial Thinning – Time Consumption and Tree Damage Parameters. *International Journal of Forest Engineering*, 16 (2), 89–99. https://doi.org/10.1080/14942119.2005.10702518

39 Magagnotti, N., Pari, L., Picchi, G. & Spinelli, R. (2012). Energy biomass from the low-investment fully mechanized thinning of hardwood plantations. *Biomass and Bioenergy*, 47 (0), 195–200. https://doi.org/10.1016/j.biombioe.2012.09.042

40 Makovskis, K., Lazdina, D. & Popluga, D. (2021). Agriculture land afforestation with fast-growing woody crops: economic evaluation according to yields of previous experimental trials. *Rural Development*, 247–251. https://doi.org/10.15544/RD.2021.044

41 Marchi, E., Magagnotti, N., Berretti, L., Neri, F. & Spinelli, R. (2011). Comparing Terrain and Roadside Chipping in Mediterranean Pine Salvage Cuts. *Croatian Journal of Forest Engineering*, 32 (2), 587–598

42 Ministru Kabinets (2018). Siltumnīcefekta gāzu emisiju aprēķina metodika, noteikumi Nr. 42 (Methodology for calculation of greenhouse gas emissions, regulations no. 42).

Latvijas Vēstnesis. 18. https://likumi.lv/ta/id/296651-siltumnicefekta-gazu-emisiju-aprekina-metodika

43 Ministru kabinets (2020). 2020. gada 4. februāra rīkojums Nr. 46 'Par Latvijas Nacionālo enerģētikas un klimata plānu 2021.–2030. gadam' (order of the Cabinet of Ministers from 04.02.2020 No. 46 on Latvia's National Energy and Climate Plan for 2021-2030). Latvijas Vēstnesis.

44 Ministry of Environmental Protection and Regional Development (2022). *Latvia's National Inventory Report Submission under UNFCCC and the Kyoto protocol Common Reporting Formats (CRF) 1990 – 2020*. Riga: Ministry of Environmental Protection and Regional Development of the Republic of Latvia. [2021-12-24]

45 Miyata, E.S. (1980). *Determining fixed and operating costs of logging equipment*. (USDA Forest Service, NC-55). North Central Forest Experiment Station: Forest Service, U.S. Department of Agriculture. https://www.fs.usda.gov/treesearch/pubs/10120 [2021-09-27]

46 Pecenka, R., Ehlert, D. & Lenz, H. (2014). Efficient harvest lines for Short Rotation Coppices (SRC) in Agriculture and Agroforestry. *Agronomy research*, 12 (1), 151–160

47 Petaja, G., Butlers, A., Okmanis, M. & Zimelis, A. (2017a). Estimation of productivity and prime cost of Logset 5HP GT harvester in thinning. *Proceedings of the 8th International Scientific Conference Rural Development 2017*, (In press). https://doi.org/10.15544/RD.2017.175

48 Petaja, G., Muižnieks, E. & Kalēja, S. (2017b). Efficiency of Vimek 610.2 forwarder and its impact on soil in forest thinning. *Proceedings of the 8th International Scientific Conference Rural Development 2017*, (In press). https://doi.org/10.15544/RD.2017.176

49 Schnorf, V., Trutnevyte, E., Bowman, G. & Burg, V. (2021). Biomass transport for energy: Cost, energy and CO2 performance of forest wood and manure transport chains in Switzerland. *Journal of Cleaner Production*, 293, 125971. https://doi.org/10.1016/j.jclepro.2021.125971

50 Scholz, V. & Lücke, W. (2007). SRC Harvesting Machinery - a Status Report. LANDTECHNIK.

51 Sirén, M. & Aaltio, H. (2003). Productivity and Costs of Thinning Harvesters and Harvester-Forwarders. *International Journal of Forest Engineering*,. https://journals.lib.unb.ca/index.php/IJFE/article/view/30212 [2022-05-07]

52 Spinelli, R., Eliasson, L. & Magagnotti, N. (2019). Determining the repair and maintenance cost of wood chippers. *Biomass and Bioenergy*, 122, 202–210. https://doi.org/10.1016/j.biombioe.2019.01.024

53 Thor, M., Von Hofsten, H., Lundström, H., Lazdāns, V. & Lazdiņš, A. (2006). *Extraction of logging residues at LVM*. Uppsala: AS Latvijas valsts meži.

54 Zalāne, L. (2022). Gada laikā gāzei cena augusi desmitkārtīgi, šķeldai – teju trīs reizes. Vai kāps mūžīgi? (During the year price of natural gas increased 10 times, of wood chips - tripled. Will it raise forewer?). *Latvijas Sabiedriskie Mediji*. https://www.lsm.lv/raksts/zinas/ekonomika/gada-laika-gazei-cena-augusi-desmitkartigi-skeldai--teju-tris-reizes-vai-kaps-muzigi.a462548/

55 Zhu, J.-J. (2008). Wind Shelterbelts. In: Jørgensen, S.E. & Fath, B.D. (eds) *Encyclopedia of Ecology*. Oxford: Academic Press. 3803–3812. https://doi.org/10.1016/B978-008045405-4.00366-9

56 Zimelis, A., Kaleja, S. & Ariko, S. (2020). Evaluation of productivity and costs of Malwa forest machine in sanitary fellings in Latvia. *Proceedings of Research for Rural Development 2020*, October 6 2020. 61–65. https://doi.org/10.22616/rrd.26.2020.009

57 Zimelis, A., Kalēja, S., Spalva, G., Saule, G., Rozītis, G. & Petaja, G. (2017a). Factors affecting productivity of Vimek 404 T5 harvester in pre-commercial thinning., Lappeenranta , Finland, 2017. 46. Lappeenranta , Finland: Scandinavian Society of Forest Economics. http://www.metsateho.fi/wp-content/uploads/Proceedings-2017.pdf

58 Zimelis, A., Lazdins, A., Kaleja, S., Spalva, G. & Rozitis, G. (2017b). Productivity of harvester Vimek 404 T5 in forest thinning in Latvia., Minsk, 2017. 36–39. Minsk: Ministry Of Education Of The Republic Of Belarus Belarusian State Technological University

59 Zimelis, A. & Spalva, G. (2022). Productivity and GHG balance of harvesting and forwarding in thinning of aspen hybrid plantations. *Engineering for Rural Development*, 537–542. https://doi.org/10.22616/ERDev.2022.21.TF181