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Time usage and efficiency of machinery during stump crushing

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Abstract. This study was carried out at a roadside landing of the Augustów Forest District in order to determine the structure of a typical working day for machines involved in stump crushing as well as the overall efficiency of the process and the machinery's fuel consumption. The machines involved in the entire process were a front-loader, a shredder, a screen and a truck-tractor unit.

Machinery activity was recorded using a sampling method with a three-minute interval. During 16 hours of observation, 533 stumps were crushed to produce 362 m^3 lv of timber particles in total and the average operational productivity reached 28 m^3 lv h^{-1}. Based on the amount of consumed fuel and its energy content, the energy input of the process was calculated to be 103.33 MJ m^{-3} lv which is 3640.53 MJ m^{-3} lv less than the output of energy gained at the power plant. Total CO$_2$ emissions of the processing machinery and transport off the forest site were estimated using previously published data and amounted to 7.58 kg m^{-3} lv.

Keywords: stump, crushing, time, energy, efficiency

1. Introduction

Global warming has a significant impact on climate change. Further, in the case of the most negative scenario (RCP 8.5), fossil fuel combustion could lead to an increase in the temperature of the Earth's surface, increasing the temperature in Europe by more than 6 °C in 2100 (IPCC 2014). This will significantly affect all ecosystems and areas of human economic activity. In reference to the Paris Agreement (COP 21), it is extremely important not only to stop the increase in the mean temperature of the Earth to under 2 °C as compared to the pre-industrial period, but also to actually limit the warming to 1.5 °C above the pre-industrial average.

The use of forest biomass as a source of energy is one of the alternatives to burning the fossil fuels, which may contribute to reducing the emission of greenhouse gases. Apart from firewood and the logging residues, tree stumps can provide an efficient source of biomass. In recent years, the amount of stump-generated energy has increased, especially in the Scandinavian countries – in Finland, about 1.1 million m^3 of shredded stump is used in boilers and power plants (Ylitalo 2013).

Previous studies on using stumps for energy purposes were conducted mainly in the northern Europe (Laitila et al. 2008, Lazdins et al. 2009), although one of the first experiments in the technology of root recovery to obtain a source of energy was carried out in Italy (Spinelli et al. 2005). Experiments have also been conducted in the USA on extracting stumps from soil, among others, using excavators equipped with grapples designed for construction demolishing (Mitchell 2009) and mobile shredders to process logging residues and whole trees for energy chips (Anderson et al., 2012). Many analyses have been conducted on the economy of using stumps (Eriksson, Eliasson 2015; Eriksson et al. 2014; Laitila et al. 2015), but the studies also considered issues of an ecology and the environmental impact of such activities (Moffat et al. 2011; Berg et al. 2015).

The purpose of this study was to determine the working day structure of the machines involved in the stump crushing process, the total efficiency of this process, and the fuel consumption (including transport to a combined heat and power – CHP – plant), as well as the balance between the input needed for the logging process and the energy output of burning this biomass.

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2. Materials and methods

The research was carried out at a temporary roadside landing in the Żyliny Forest District (Augustów Forest Inspectorate). The stumps were extracted from clear-cuts intended to become wildlife food plots, which required the area to be grubbed up after removing the stand. The stumps were removed from the ground by an excavator and transported from the plots to the landing by a forwarder; however, this stage was not part of the analysis of the present study. The stumps were stacked up to two meters high or laid side by side and seasoned for a period of 10 months.

The characteristics of the stand before the area was adapted for game plot are presented in Table 1.

The diameter (in the place of a felling cut) of a sample of 100 stumps was measured (Figure 1), with each stump successively removed by a tractor's grapple from various locations in the stack.

There were four machines involved in the stump shredding process: the Doosan DL 250 wheel loader, the Doppstadt DW 3060 slow speed shredder, the Doppstadt SM 518 single-drum screen and the MAN 27.463 tractor equipped with a hydraulic manipulator with a grapple.

All machines were operating at the same time, forming a production line. The wheel loader performed several tasks: moving the stump from the stack to the nearby tractor unit, moving and then loading the shredded and sifted chips to the transport means, removing the dirt from under the screen (mostly sand) and levelling the material at the landing, as well as changing the location of the shredder and screen at the landing. The task of the tractor unit was to load the stump into the shredder and to move the shredder and screen over long distances. As the shredder and screen were working almost all the time in an automated way, two persons − the drivers of the wheel loader and the tractor unit – sufficed to handle the process. All machines had a time category called the 'long-distance travel'. This is the time spent moving the machines from the landing to the garage and between the various roadside landings within the forest district. The necessity of recording this time was due to the desire to show the amount of energy and working time expended, when it was not possible to leave the machines in the forest for the night because of the fear of fuel and parts being stolen, which also prolonged the time spent on preparatory and completion activities, as well as hauling the shredder and screen by the tractor.

The biomass from the forest to the storage area at the CHP plant in Bialystok was transported over a 172 km (two-way) route with the Scania R580 trucks hauling two containers with an average capacity of 36 m^3lv each.

Snapshot observations were used to determine the contribution of each machine activity. Observations were made

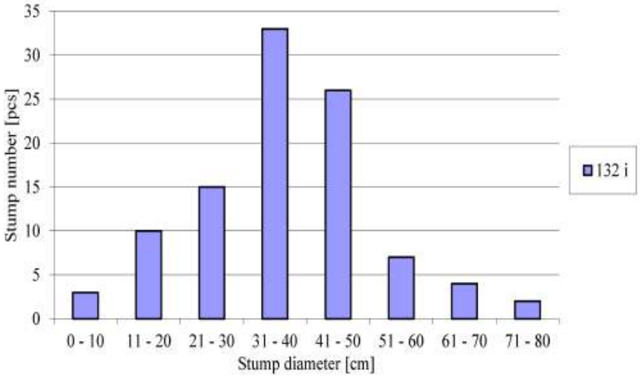

Figure 1. Number of stumps in diameter ranges based on the sample from the shredding site

Table. 1. Stand characteristics of the source of stumps, before clear cutting

Location	Forest site type	Layer	Share, species	Age	Stocking	Canopy density	DBH	Height	Site Index	Quality	Stand volume per 1 ha
Żyliny, 132i	BMw	main stand	4 Brz	89	0.8	broken	28	27	I	2	129
			2 So	89			35	24	I.5	2	71
			2 Św	89			34	24	II.5	2	48
			2 Św	63			21	19	II	3	71
		undergrowth	Św	23	0.1			6		22	
			1 Św	64			21	17	II.5	4	20

Explanation: BMw – moist mixed coniferous forest, Brz – silver birch, So – Scots pine, Św – Norway spruce every 3 minutes for two full working days. Applying this time interval allowed a precise determination of the actions performed successively by all the machines and provided the time to make the entry in the field recorder while maintaining a high repeatability of the measurements (20 observations per hour). Fuel consumption was determined from the readings of the machines' onboard computers and CO_2 emissions were calculated on the basis of the values contained in the publication of the Ministry of the Environment (Fuel values..., 2015). Operational efficiency was selected to estimate the energy input because this kind of efficiency category includes those activities of a working day in which engines are running. Also, the environmental impact was calculated based on the fuel consumed during the main operations and changing the location of the machines at the roadside landing.

In order to obtain an image of the actual efficiency of the forestry machines used, the balance of their operating time was calculated based on the terminology of the National Forest Machinery System (Botwin 1993). The coefficient of general work shift time use was the ratio of the main times (e.g., shredding, sieving or stump loading) to the total time. The coefficient of working time use determined the ratio of the main times to the sum of the main times, change in the work site within a given roadside landing, preparation-completion time (setting up elements of the machines, the configuration to start work) and the time spent repairing equipment. The coefficient of operational time use is defined as the ratio of the main times to the sum of the main times and the time required to change the work site. The technical-technological robustness coefficient was directly related to the time needed for repairs (the ratio of main times to the sum of main times and repair times), and the technical maintenance robustness coefficient − respectively − with preparation-completion time and maintenance time (regulating machines, configuration during work and refuelling).

Input and emissions generated by transport vehicles, based on previous research conducted in the Augustów Forest (Gałęzia 2013a), were used to calculate the sum of energy input and the total CO_2 emissions.

The amount of energy input was compared with the energy values of the four representative samples of the raw material, taken successively (every 4 hours) from the stack of wood chips behind the screen. Samples were analysed for calorific value, total moisture content, ash content and sulphur content.

3. Results

A total of 16 hours and 6 minutes of work conducted by the set of machines was recorded. During this time, 533 stumps were crushed to obtain 362 m^3lv of wood chips. The replacement coefficient of the number (pieces) of stumps per m^3lv ranged from 0.54 to 0.77. The operating efficiency of the whole stump crushing process was between 33.95 pcs h^{-1} and 37.62 pcs h^{-1}.

More than half of the wheel loader's time was used to move the stumps near the shredder (Figure 2), by moving them in the bucket or (less often) by pushing them. Other tasks qualified as the main times were: moving and levelling the soil separated from the chips during screening, transferring the sifted wood chips to a separate pile and loading the wood chips onto the container trucks for transport. The aggregate share of main times was 84%. The 4% share of the long-distance travel was due to the need to transport chips prepared earlier at a different roadside landing distant more than one kilometre away from the current workplace.

The low speed rotary shredder had only one main operation − shredding the stumps, which occupied 80% of its working time, as was in the case of the drum screen, where the separation of debris from the chips took 81% of the working time. Both machines worked in automatic mode, closely linked, so the structure of their working time was almost identical.

In the structure of the working time of the tractor equipped with a grapple, the main operation of feeding stumps to the shredder dominated (76%). 3% of this vehicle's working time was spent moving the shredder and screen between landings.

Based on the data obtained during field measurements, the selected working time coefficients were determined and labour productivity was calculated based on the methods provided by Botwin (1993). The working time use coefficient was slightly lower than the operational time use coefficient because it includes not only the time for changing a work place, but also the time taken for repairs and preparation and completion.

Energy input and carbon dioxide emissions generated by individual machines were also calculated (Table 2).

In order to calculate the total energy input and the total CO_2 emission of the process, the input and emissions generated by the means of transport were taken into account. The energy input of the machines operating at the roadside landing, that is, 63.05 MJ m^{-3}lv, was increased by 40.28 MJ m^{-3}lv, resulting in 103.33 MJ m^{-3}lv. Similarly, in the case of CO_2 emissions, the specific emissions of four machines at 4.63 kg m^{-3}lv were increased by emissions of 2.95 kg m^{-3}lv resulting from the transport of chips, to yield a total of 7.58 kg m^{-3}lv.

The samples of chips taken for analysis allowed certain biomass parameters to be assessed. The average results of four samples of shredded raw material in its working condition were as follows: calorific value 15545.00 MJ t^{-1}, total moisture 13.30%, ash content 9.79%, sulphur content 11.40%. The biomass density was an average of 301.05 kg m^{-3}lv, which when considering the efficiency of the power

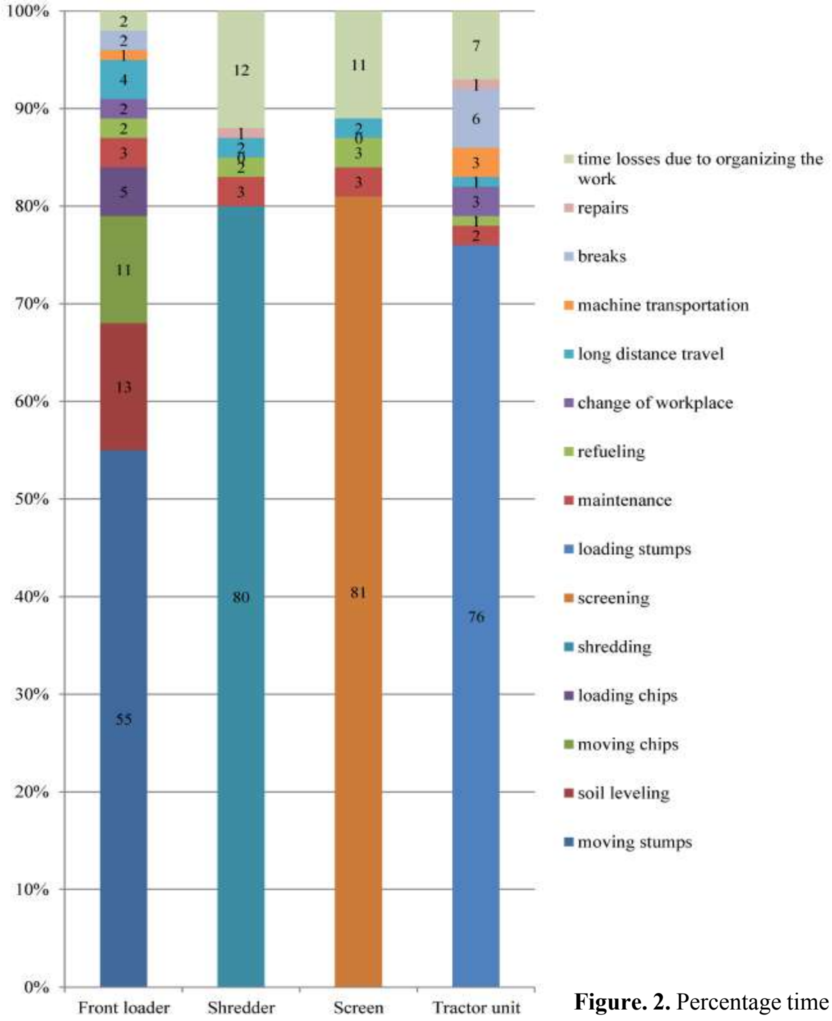

Figure. 2. Percentage time share of operations performed by machinery

plant at 80% (Gałęzia 2013a), provided an energy effect of 3743.86 MJ m^{-3}lv.

4. Discussion

Obtaining biomass from stumps requires the use of machines other than the already popular systems in Poland of slash-bundling or chipping logging residues. Insofar as the set of machines always has to include one to crush stumps, various other technologies allow it to be integrated with a screen (Laitila, Nuutinen 2013) or to resign from using a separator (Lazdins et al. 2009). It is also possible to aggregate a single shredder and screen into one machine and mount them on the chassis of a tractor equipped with a gripper (Nuutinen et al., 2014), which, with a properly prepared stack of stumps, allows the number of operators to be reduced to one.

The use of modern equipment, in the form of a partially automated production line, allowed very high-performance coefficients to be achieved. The operational time use coefficient ranged from 0.96 to 1.00 for individual machines, which is significantly better than slash-bundling system, which had the coefficient varying from 0.79 to 0.92 (Gałęzia 2013b). Also, the technical-technological robustness coefficient, despite the need for minor repairs (6 minutes to repair a feeder cable in the shredder and 12 minutes to replace a broken hydraulic hose in the tractor), demonstrates the high quality of the equipment and the fact that the operators maintain it in proper condition, which in turn minimizes repair costs (ranging from € 11.2 mh^{-1} for forwarders to € 20.2 mh^{-1} for harvesters); however, it is difficult to find a correlation between repair costs and the average annual working time of such machines (Holzleitner et al. 2011).

Table. 2. Coefficients of time use, labor efficiency, energy input and carbon dioxide emissions during stump crushing

Characteristics of efficiency	Front loader	Shredder	Screen	Tractor unit
General work shift time use coefficient	0.85	0.80	0.81	0.76
Working time use coefficient	0.95	0.96	0.96	0.93
Operational time use coefficient	0.98	1.00	1.00	0.96
Technical-technological robustness coefficient	1.00	0.99	1.00	0.98
Technical maintenance robustness coefficient	0.95	0.94	0.93	0.96
Operational productivity [m^3 lv h^{-1}]	27.42	28.50	28.28	28.50
Working productivity [m^3 lv h^{-1}]	26.81	27.53	27.32	27.63
Exploitation productivity [m^3 lv h^{-1}]	23.13	22.98	23.06	22.41
Energy input [MJ m^{-3}(p)]	13.24	31.74	6.35	11.72
CO_2 emission [kg m^{-3}(p)]	0.97	2.33	0.47	0.86

The values of the operational productivity of individual machines obtained in this study are similar and the technical-technological robustness coefficient is close to 1.00, which allows us to determine the overall system efficiency at 28 m^3lv h^{-1}. This is four times less than the fully integrated Crambo 6000 machine (Laitila, Nuutinen 2013) and two times less than a CBI 5800 quick rotary shredder (Nuutinen et al., 2014). In the case of crushing stumps with stationary grinders at the terminal, their efficiency is about 15% higher (10 t d. m. $^{h-1}$) (Lazdins et al. 2009). The reason for this low productivity can be the relatively large share of time lost in organising the work, which was due to the multi-functionality of the wheel loader. The need to load the transport vehicles (also in a landing other than the one where the shredding took place) affected the share of long-distance travel to a greater degree than for the other machines. This resulted in downtime across the production line and had a noticeable effect on the efficiency of the process.

Although the observations have shown that the efficiency of the screen is slightly lower (0.22 m^3lv h^{-1}) than that of the shredder, there was no record of a situation where the screen caused a loss of work time. While its use in fact led to an increase in energy input by about 6%, it also contributed to the improved quality of the product produced. Sieving at the roadside landing also has a positive effect on the efficiency of transporting the wood chips, reducing their mass by the proportion of the separated debris (Eriksson, Eliasson 2015).

The obtained results of the biomass parameter measurements differ from those published by other researchers. Laurila and Lauhanen (2010) obtained an ash content at 1.7% for stumps that had seasoned for 36 months, while Laitila and Nuutinen (2015) – between 1 and 1.5% for stumps seasoned from 10 to 20 months. These results are much lower than those obtained in the Augustów Forest (9.79%). This is because those studies analysed clean wood from tree trunks, whereas the chips from the stumps had a significantly higher ash content – 12.9% (Nuutinen et al., 2014) and even 14% (Alakangas 2000). The calorific value of the wood from spruce stumps harvested in Western Finland after a three year storage period was 5680 MJ m^{-3}lv (Laurila, Lauhanen 2010), which is 1000 MJ m^{-3}lv more than in the case of the Augustów Forest, but the chips from the spruce stumps (Nuutinen et al. 2014) had a calorific value close to the one obtained in Poland (16.4 MJ kg^{-1} compared to 15.5 MJ kg^{-1}). Bergström and Matisons obtained higher values for stumps from mineralised soil (17.1 to 17.9 MJ kg^{-1}), but significantly lower calorific values (14.3 MJ kg^{-1}) were found for stumps obtained from wetlands (Forest refine ... 2014).

Differences in ash content and calorific value can be generated not only by the different species composition of the stumps, but also by their exposure to atmospheric factors, particularly rainfall, which helps to wash the stump of mineral debris, thereby reducing the risk of damaging the shredders, as well as obtaining lower boiler efficiencies (Otepka 2013). Biomass is also affected by atmospheric humidity, especially in the climate of northern Europe, where there is a significant correlation between moisture in the wood and the seasons (Laurila, Lauhanen 2010).

5. Conclusions

Research has shown that stumps can be an effective source of biomass energy. Despite the involvement of a number of machines in the production process, this activity is justified by the energy balance obtained. A low speed shredder and a screen are characterised by high reliability, and the raw material produced has an energy value similar to firewood.

Conflict of interest

The author declares no potential conflicts of interest.

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