Efficiency of Integrated Grinding and Screening of Stump Wood for Fuel at Roadside Landing with a Low-Speed Double-Shaft Grinder and a Star Screen

Juha Laitila, Yrjö Nuutinen

Abstract

Impurities in harvested stumps are a quality problem because high levels of mineral contaminants decrease the effective heating value of the stump wood, and can also affect ash melting behaviour during combustion, leading to sintering and drift problems. The aim of this case study was to clarify the productivity and screening efficiency of the Kompetech Crambo 6000 low-speed double-shaft grinder equipped with a Komptech star screen, in the integrated grinding and screening of Norway spruce and Scots pine stumps for fuel at a roadside landing, when using two different sieve sizes (250 x 320 mm and 180 x 180 mm screen baskets). Furthermore, we studied the fuel consumption of the Crambo 6000 grinder, ash content and particle size distribution of ground stump wood, and ash content and particle size distribution of the screening reject. In addition, the heating value of the produced hog fuel and screening reject were analysed. During the time of the studies, both the grinder and star screen were operating well and there were no delays due to machine breakdowns. The mobile Crambo 6000 grinder was also capable of operating well in constricted roadside landings. The quality of the produced hog fuel was high, due to low ash content (0.4–2.3%), and this highlights the significance of screening to guarantee sufficient quality when processing stump fuel. The ash content of the screening reject was 32.4–74.7%, and the effective heating value was 5.2–13.4 MJ/kg. The effective heating value of the produced hog fuel was 17.9–19.9 MJ/kg. The average grinding productivity, when using the 250 x 320 mm screen basket, was 162 loose m^3 per effective hour, and the fuel consumption of the grinder was 0.44 litres per loose m^3. With a narrower screen, the average grinding productivity was 101 loose m^3 per effective hour, and the fuel consumption of the grinder was 0.75 litres per loose m^3.

Keywords: grinding, screening, stump wood, quality, procurement system, buffer-storage, hog fuel

1. Introduction

The harvesting of stumps for energy generation in Finland has increased rapidly during the past ten years. The previous time when stumps were lifted was in the 1970s and in the early 1980s, when they were procured as raw material for either sulphate chemical pulp or energy generation (e.g. Hakkila 1976, Kuitto 1984, Hakkila 2004). However, high harvesting costs made this unprofitable, and the use of stumps came to an end. Stump harvesting was reintroduced ten years ago, when UPM Forest commenced the harvesting of Norway spruce (*Picea abies* (L.) H. Karst.) stumps, along with logging residues and small-diameter trees from thinnings, for delivery to the combined heat and power (CHP) plant of Jämsänkoski paper mill in Central Finland (Markkila 2005, Backlund 2007). Although it was initially met with scepticism, the use of stump wood in energy generation then spread to other parts of the country, and in 2012, some 1.1 million m^3 of comminuted stump wood were consumed by heating plants and power plants (Ylitalo 2013), with the total techno-economical harvesting potential estimated to be 5.0 million m^3 per year (Kärhä et al. 2010b).

Coniferous rootstock is considered to be a promising energy source because it contains higher concentrations of the energy-rich components – lignin and extractives, than stem wood (Hakkila 1975, 1976). Norway spruce is the most interesting species for stump harvesting because it is easier to harvest and clean than Scots pine (*Pinus sylvestris* L.) (Nylinder 1977, Hakkila 2004). The root system of Norway spruce spreads out close to the ground surface; it has no taproot and the lateral roots are thicker and longer than those of Scots pine (Hakkila 1976). Impurities in the harvested stumps are a quality problem, as usually the stumps and roots include some rocks and soil (Spinelli et al. 2005, Laitila et al. 2010, Laurila and Lauhanen 2010). The effective heating value of wood biomass is the main parameter defining its quality as fuel. Ash content is one of the major factors decreasing the calorific value of the stump wood, and high levels of mineral contaminants can also affect ash melting behaviour during combustion, leading to sintering and drift problems (Anerud and Jirjis 2011, Anerud 2012).

The stumps are uprooted and split using a tracked excavator equipped with a stump extraction head (e.g. Backlund 2007, Karlsson 2007, Laitila et al. 2008, Hedman 2008, Lazdins et al. 2009, Jouhiaho et al. 2010, Lindroos et al. 2010, Laitila 2010, Anerud and Jirjis 2011, Erkkilä et al. 2011). The splitting of stump wood into pieces accelerates its drying and increases the productivity of the comminution work. Furthermore, the risk of impurities is higher when the stump is not split properly. Excavators of about 20 tons are used in stump harvesting (Laitila 2010). After seasoning at the stand, stumps are forwarded to roadside landings by forwarders (e.g. Backlund 2007, Karlsson 2007, Laitila et al. 2008, Lazdins 2009, Laitila 2010). Harvested stump and root wood dries fast during spring and summer, and moisture content (wet basis) can decrease from 53% to 31% even in one month (Laurila and Lauhanen 2010). If Norway spruce stump wood has dried well once, water absorption is very weak and the moisture content increases only slightly in the late autumn (Laurila and Lauhanen 2010). Dry matter losses of 4% due to decay, during 1 year of storage, have been reported by Nylinder and Thörnqvist (1981), and during 3 months of storage, dry matter losses of stump wood have been in the range of 1.5–3.4% of dry weight (Anerud and Jirjis 2011).

Stumps are comminuted with grinders, as the blunt tools are less sensitive to the wearing effect of contaminants such as mineral soil and stones (Rinne 2010, Spinelli et al. 2012, Eriksson et al. 2013). However, grinders offer a rather coarse product, unsuitable for use especially in some smaller plants (Strelher 2000, Rinne 2010, Eriksson et al. 2013). In contrast, chippers with sharp tools are exclusively applied to clean wood and offer a more consistent product (Rinne 2010, Spinelli et al. 2011, Spinelli et al. 2012, Eriksson et al. 2013). In Finland, the majority of stumps are ground either at the plant or at terminals, whereas the majority of small-diameter trees and logging residues are chipped at roadside landings (Strandström 2013). Until now, comminution of stumps has been done with heavy, often stationary grinders. In smaller plants, due to small comminution volumes, the construction of a stationary grinder is not economically feasible (Laitila et al. 2010). In addition, the transportation of stumps calls for a biomass truck with solid side panels and bottom, and economical transport distances are short, owing to the small potential payloads (Ranta and Rinne 2006, Laitila et al. 2010). The relative bulk density of an intact rootstock pile is of the order of 0.1, whereas that of chopped stumps is 2 to 4 times greater (Hakkila 1976). As stump parts are hard and can damage the sides of the truck, the truck must be made of strong material, which increases the kerb weight of the truck-trailer unit. Recently, effective mobile grinders suitable for the comminution or pre-comminution of stumps at roadside landings have been introduced (von Hofsten and Granlund 2010, Kärhä et al. 2011, Laitila et al. 2013). The truck- or semitrailer-mounted grinder is used in a similar manner to mobile chippers in the chipping of logging residues and small-diameter trees. The grinder moves from landing to landing, with the comminuted material transported to the end-user by truck (Asikainen 2010).

According to an expert survey (Laitila et al. 2010), two major problems that can limit the growth of stump wood procurement for fuel are: 1) stump particles remain too large when applying current harvesting technologies, resulting in the truck load containing too much air, so that, in terms of weight, the trucks seldom reach maximum payload; 2) stump wood deliveries contain contaminants, which reduce the calorific value, can cause problems in combustion, and might thus limit the share of stump wood in the fuel mix of power and heating plants. There is also a need to develop logistic models for procurement and storage, because supply and demand for fuels is often diachronic, and screening of stump wood is more effective when material is unfrozen (Laitila et al. 2010). During the cold season of the year, the comminuting machinery and transportation equipment are in intensive use, while during the summer months, the problem is a lack of work (Laitila et al. 2010). In order to guarantee a reliable supply of fuels from roadside landings during the cold season, there is an obvious need to store comminuted stump wood in buffer stacks at terminals and plants for at least a few weeks before combustion (Laitila et al. 2010).

One way to increase the payload and reduce the contaminant content of fuel chips is integrated comminuting and screening of stumps or logging residues at roadside landings (Anerud 2012, von Hofsten et al. 2012, Fogdestam et al. 2012, Eriksson et al. 2013, Dukes et al. 2013). This approach would reduce the amount of fine material contaminants at the source, provide a possibility to increase payloads and lower transportation costs, and at the same time increase the quality of the produced fuel (Anerud 2012, von Hofsten et al. 2012, Eriksson et al. 2013, Dukes et al. 2013). In a study, Laitila et al. (2013) found that the heating values of the finest stump wood hog fuel particles were significantly lower compared to larger particles, due to high contaminant and bark content.

The recently introduced semitrailer-mounted Komptech Crambo 6000 low-speed double-shaft shredder equipped with a Komptech star screen is a novel mobile grinder unit, which is capable of operating both at terminals and roadside landings and of producing hog fuel with lower fine and contaminant content than usual (http://www.komptech.com). Currently, there is one Crambo 6000 grinder equipped with a Komptech star screen operating in Finland. Many questions are raised that must be addressed quickly in order to overcome possible bottlenecks. If comminution of stumps at roadside landings is becoming more common, there is also an urgent need to get information about storing comminuted stump wood in buffer stacks of plants and terminals.

1.1 Aim of the study

The aim of this case study was to clarify the productivity and screening efficiency of the Crambo 6000 grinder equipped with a star screen in the integrated grinding and screening of Norway spruce and Scots pine stumps for fuel at a roadside landing, when using two different sieve sizes (250 x 320 mm and 180 x 180 mm screen baskets). Furthermore, we studied the fuel consumption of the Crambo 6000 grinder, ash content and particle size distribution of ground stump wood, and ash content and particle size distribution of the screening reject. The heating value of the produced hog fuel and screening reject were also analysed. In addition, we measured the self-warming of ground stump wood during 64 days of storage at the buffer stack in the terminal, from 6th August 2013 to 10th October 2013.

2. Material and methods

2.1 The time study of integrated grinding and screening of stump wood for fuel

The time study data consisted of 20 semitrailer loads of comminuted stump wood originating from five different stands located in Juva (61°54'N, 27°47'E), Eastern Finland (Table 1), and the studies were carried out during daylight hours from 5th to 8th August 2013. The observation unit was a semitrailer with a 90 m^3 load volume, and each load was always completely filled by conveyer belt and levelled with a shovel. The ground materials were Scots pine and Norway spruce stumps, which had been uprooted and split by an excavator-based stump harvester. Small stumps (diameter < 30 cm) had been split into two pieces, while larger stumps were split into three or four pieces. The average stump diameter was measured to be 40 cm. The storage time of stumps at the roadside landing before comminution was in the range of 10–20 months (Table 1). In the trials, the Crambo 6000 grinder was equipped with 250 x 320 mm and 180 x 180 mm screen baskets, and 10 semitrailer loads were comminuted using both sieve sizes (Table 1). The use of 180 x 180 mm and 250 x 320 mm screen baskets gave a granularity that requires secondary grinding either at the terminal or at the plant before combustion.

From the roadside landing comminuted stump wood, 6 loads were transported to the CHP plant, and 14 loads to the terminal. The CHP plant was located in Mikkeli (61°41'N, 27°17'E) and the terminal in Pieksämäki (62°15'N, 27°12'E), Eastern Finland. The payloads of the semitrailer loads that were transported directly to the CHP plant were measured with a certified weight scale at the plant, and both the filled and empty weights of the semitrailers were recorded. Unfortunately, at the Pieksämäki terminal or nearby, a certified weight scale was not available in trim. Therefore, the experimental setup was based on using the semitrailer with a 90 m^3 load volume as the base unit for productivity measurements and comparison of different treatments.

The fuel consumptions of the Crambo 6000 grinder and towing vehicle were measured at a local fuel station after changing screen baskets, at the end of every second grinding day. The mobile grinder and towing vehicle were parked in exactly the same place both times, and the fuel tanks were refilled to full. The accuracy of the fuel pump was 0.1 litres.

The mobile industrial grinder used for the experiment was a tandem-axle semitrailer-mounted Crambo 6000 grinder equipped with a star screen (Fig. 1 and Fig. 2). The grinder was driven independently

Table 1 Properties of the ground material per semitrailer load

Sequence number of loads	Ground material & storage time in months	Size of screen basket, mm	Moisture content of stump wood, %	Volume, m^3 & payload, kg	Basic density of stump wood, kg/m^3
1	Norway spruce & 11	250 x 320	17.9	90 m^3 loose	461
2	Norway spruce & 11	250 x 320	20.9	90 m^3 loose	466
3	Scots pine & 20	250 x 320	23.9	90 m^3 loose	417
4	Scots pine & 20	250 x 320	31.5	90 m^3 loose	435
5	Scots pine & 20	250 x 320	33.7	90 m^3 loose	440
6	Scots pine & 20	250 x 320	29.8	90 m^3 loose	452
7	Scots pine & 20	250 x 320	20.9	90 m^3 loose	446
8	Norway spruce & 10	250 x 320	23.9	90 m^3 loose	440
9	Norway spruce & 10	250 x 320	22.2	90 m^3 loose	420
10	Norway spruce & 10	250 x 320	21.2	90 m^3 loose	431
11	Norway spruce & 12	180 x 180	32.7	90 m^3 loose & 13 900 kg	430
12	Norway spruce & 12	180 x 180	32.8	90 m^3 loose & 14 800 kg	409
13	Norway spruce & 12	180 x 180	35.4	90 m^3 loose & 14 100 kg	419
14	Norway spruce & 12	180 x 180	36.7	90 m^3 loose & 15 000 kg	447
15	Norway spruce & 12	180 x 180	27.8	90 m^3 loose & 14 300 kg	418
16	Norway spruce & 12	180 x 180	23.1	90 m^3 loose & 13 050 kg	440
17	Norway spruce & 11	180 x 180	26.5	90 m^3 loose	435
18	Norway spruce & 11	180 x 180	27.2	90 m^3 loose	432
19	Norway spruce & 11	180 x 180	23.1	90 m^3 loose	442
20	Norway spruce & 11	180 x 180	25.1	90 m^3 loose	392

and it was powered by a 429 kW CAT C18 six-cylinder diesel engine. The grinder year model was 2011. The towing vehicle was a three-axle Volvo FM 12 (year model 2004) and the tractor was equipped with a heavy-duty Kesla 2012T cab timber loader, used to bring the wood to the vertical-flow in-feed hopper (Fig. 1 and Fig. 2). The timber loader was equipped with a five-spike grapple developed for handling stumps and logging residues (Fig. 2). The star screen deck underneath the screen baskets separated off the fine fractions, which were removed back to the landing area via a side conveyer belt (Fig. 1 and Fig. 2), whereas the coarse fraction was considered to be fuel. The width of the forest roads and ditches beside the ground stump wood piles were 4 m and 1 m, respectively.

The area of the in-feed hopper measured 2000 mm in width and 2820 mm in length, and the two shredding drums were located at the bottom of the in-feed hopper. The lengths of the shredding drums were 2820 mm, the drum diameter was 610 mm, and the maximum rotation speed of the drums was 0.68 s/r (41 rpm). The sickle teeth seized the material and pressed it, in a splitting action, against the cutting edge and screen baskets located underneath. The material did not exit the shredding area until the particle size matched the hole size of the screen basket, enabling the quantity of ground material of the desired particle size to be maximized. Ground stump wood was discharged into the walking floor semitrailer via a conveyer belt, and the semitrailers were located in a consecutive line (Fig. 2) or crossways to the Crambo 6000 grinder. In time studies, the semitrailers were located almost invariably (16 loads out of 20) in a consecutive line to the grinder. The skilful operator had extensive working experience. He had fifteen

Fig. 1 The tandem-axle semitrailer-mounted Crambo 6000 low-speed double-shaft grinder equipped with a star screen and heavy-duty Kesla 2012T cab timber loader

Fig. 2 Integrated grinding and screening of stumps for fuel at the roadside landing (ground stump wood was discharged into a walking floor semitrailer via a conveyer belt, and screening reject was removed back to the landing area via a side conveyer belt)

years of working experience in truck-transporting industrial roundwood, and almost three years of working experience in grinding stumps with a Crambo 6000 grinder. The total weight of the mobile grinder-truck-trailer unit was 40 tons, and that of the grinder unit was 22 tons.

The time study was carried out manually using a Rufco-900 field computer (Nuutinen et al. 2008). The working time at the worksite was recorded by applying a continuous timing method, by which a clock runs continuously and the times for different elements are separated from each other by numeric codes (e.g. Harstela 1991). The accuracy of the Rufco-900 field computer was 0.6 s (Nuutinen et al. 2008). The grinder working time was divided into effective working time (E_0h) and delay time (Harstela 1991), which is a common method employed in Nordic work studies. Auxiliary times (e.g. planning of work and preparations) were included in the work phases in which they were observed. Effective working time was divided into the following main work phases, in order of priority:

- ⇒ Loading: The work cycle began when the grapple started to move towards the stump stack and ended when a stump bunch had been lifted and placed in the in-feed hopper of the grinder. The number of grapple loads for each semitrailer load was counted, in order to calculate the average size of the grapple load in feeding.
- ⇒ Grinding (loading is idled): Began when the stump bunch had been lifted and placed in the in-feed hopper of the grinder, the in-feed hopper was full, and the shredding drums were processing wood into pieces. The work phase ended when the grapple started to move towards the stump stack or the back doors of the semitrailer had to close.
- ⇒ Moving of the semitrailer and lifting of the conveyer belt: Began when the load of the semitrailer was almost full of comminuted wood and the back doors had to close. The work phase ended when the back doors were closed, the conveyer belt was lifted higher, and the grapple started to move towards the stump pile or the shredding drums started to process the wood into pieces.
- ⇒ Arrangements: Repositioning of stumps at the roadside pile in order to improve loading work, or shaking off stones or other noticeable impurities.

Delays or preparation time: Time not related to productive grinding work, but for which the reason for the interruption was recorded. The main reasons for delay times shorter than 15 minutes were preparing the grinder for grinding work, moving machines and vehicles at the roadside landing, cleaning the dropped material and grinding residues away from the road, organisational delays (e.g. telephone calls), and personal breaks. The data analysis was conducted for productive time only (E_0h), in order to avoid the confounding effect of delay time, which is typically erratic (e.g. Spinelli and Visser 2009, Eliasson et al. 2012, Holzleitner et al. 2013). The productive time (E_0h) included the work phases of loading, grinding, and arrangements.

2.2 Sampling and laboratory analyses of ground stump wood and screening reject

Stump wood samples were taken directly from the arriving semitrailers as part of the normal delivery process in the yard of the terminal or plant, after unloading comminuted wood to the ground (Uusvaara 1978, Uusvaara and Verkasalo 1987). Samples were taken to define the moisture content, basic density, dry weight of the hog fuel, particle size distribution, ash content, and effective heating value of comminuted stump wood, and samples were analysed in the laboratory of the Finnish Forest Research Institute according to the following standards: SFS-EN 14780, SFS-EN 14774-1, SFS-EN 14774-2, SFS-EN 14774-3, SCAN-CM 43:95, SFS-EN 15149-1, SFS-EN 14775, and SFS-EN 14918. The solid content of the weighed stump wood loads (%) was based on the relation of the recorded dry masses (kg), dry green densities (kg/m^3), and frame volumes of each load (e.g. Kanninen et al. 1979, Uusvaara and Verkasalo 1987).

Four samples were taken for each semitrailer load, and wood samples were stored in plastic bags, which were carefully closed and marked. Moisture samples were packed in double bags in order to minimise the risk of bag outbreak or evaporation. The dimensions of the plastic bags were 35 x 35 cm (volume 8 litres), and the raw material, date, and time were written on the label. In addition, plastic bags were wrapped in a plastic sack, and each semitrailer load was packed in a corrugated paperboard box of its own. The samples were extracted from several locations from the load using a small shovel, so that the results would be representative of the load.

The amount, volume, and properties of the screening reject were analysed from semitrailer loads 1, 4, 9, and 15 (Table 1). A tarpaulin was placed underneath the star screen conveyer belt, in order to recover the screening reject of the integrated grinding and screening process (Fig. 3). The volume of the screening reject was measured by shovelling it into certified 90-litre boxes. From each load, a sample was taken to define the moisture content, weight, particle size distribution, ash content, and heating value of the screening reject according to standards SFS-EN 14780, SFS-EN 14774-1, SFS-EN 14774-2, SFS-EN 14774-3, SFS-EN 15149-1, SFS-EN 14775, and SFS-EN 14918. The samples were taken immediately after grinding, with a shovel, in a 10-litre plastic bucket, and the location, date, material, and time were written on the cover. The bucket and cover were sealed with adhesive tape, in order to prevent the screening reject from drying. The sample was extracted from four points in the middle of the screening reject mound, so that the results would be representative of the load.

Fig. 3 A mound of screening reject from the first semitrailer load, on a tarpaulin, after integrated screening and grinding of stumps at a roadside landing

2.3 Buffer storage of ground stump wood at a terminal stack

The temperature of the ground material at the terminal stack was monitored with four a-Nap 100 temperature loggers, from 6th to 10th August 2013. The temperature loggers were placed in the middle of the stack at 1.0 m and 2.0 m depths, in sealed plastic tubes (diameter 32 mm), and recorded the temperature once an hour. The height of the terminal stack was 4.2 m, width 15 m, and length 70 m. The temperature loggers were fully protected against dust and dirt, and they were capable of measuring temperatures from -30°C up to +85°C. The programming of the temperature loggers and the reading of data after a monitoring period of 64 days 17 hours were done with a special Windows application.

3. Results

3.1 Grinding productivity and fuel consumption

The average grinding productivity, when using the 250 x 320 mm screen basket, was 162 loose m^3 per effective hour, and the fuel consumption of the grinder was 0.44 litres per loose m^3 (Fig. 4). Grinding productivity varied in the range of 126–192 loose m^3 per effective hour, and the grapple load size in the feeding was 0.9–1.1 loose m^3. The average grapple load in the feeding was 1.0 loose m^3. When using the 180 x 180 mm screen basket, the grinding productivity and the grapple load size in the feeding were lower and the fuel consumption per loose m^3 was higher compared to the 250 x 320 mm screen basket (Fig. 4). The average grinding productivity was 101 loose m^3 per effective hour,

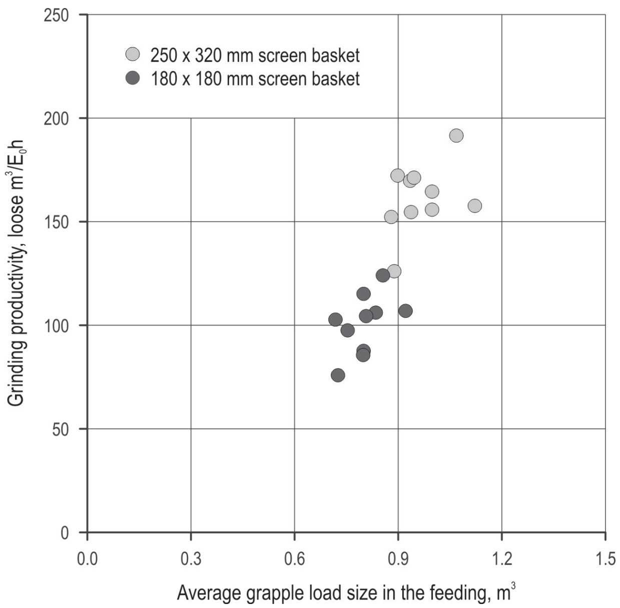

Fig. 4 Grinding productivity according to load size in the feeding, for the two screen baskets considered

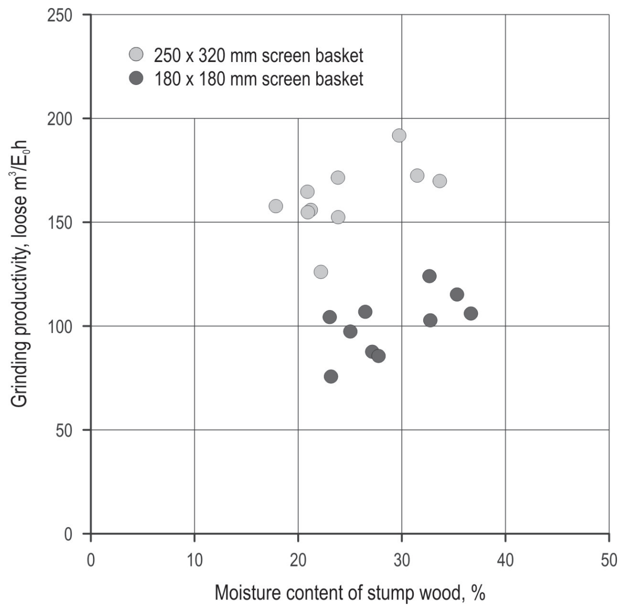

Fig. 5 Grinding productivity according to moisture content of stump wood (%), for the two screen baskets considered

and the fuel consumption of the grinder was 0.75 litres per loose m^3. Grinding productivity varied in the range of 76–124 loose m^3 per effective hour, and the grapple load size in the feeding was 0.7–0.9 loose m^3. The average grapple load in the feeding was 0.8 loose m^3.

A higher moisture percentage of the wood material improved the grinding productivity (Fig. 5), whereas the basic density of stump wood (kg/m^3) had no observed impact on grinding productivity when the basic density of the wood material was in the range of 392–466 kg/m^3. A denser 180 x 180 mm screen basket lowered the grinding productivity, and due to that, the in-feed loading was idled for, on average, 38% of the productive grinding time (min. 31% and max. 47%).

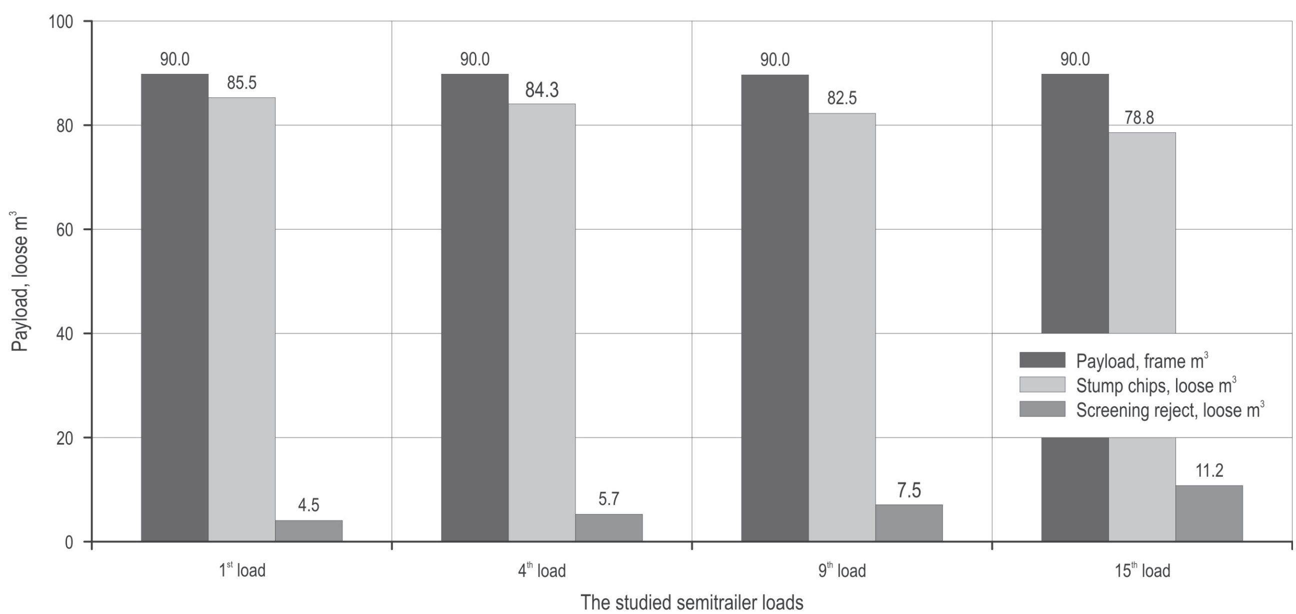

Fig. 6 The volume of screening reject per studied semitrailer load (a screen basket of 250 x 320 mm was used for loads 1, 4, and 9, and 180 x 180 mm for load 15)

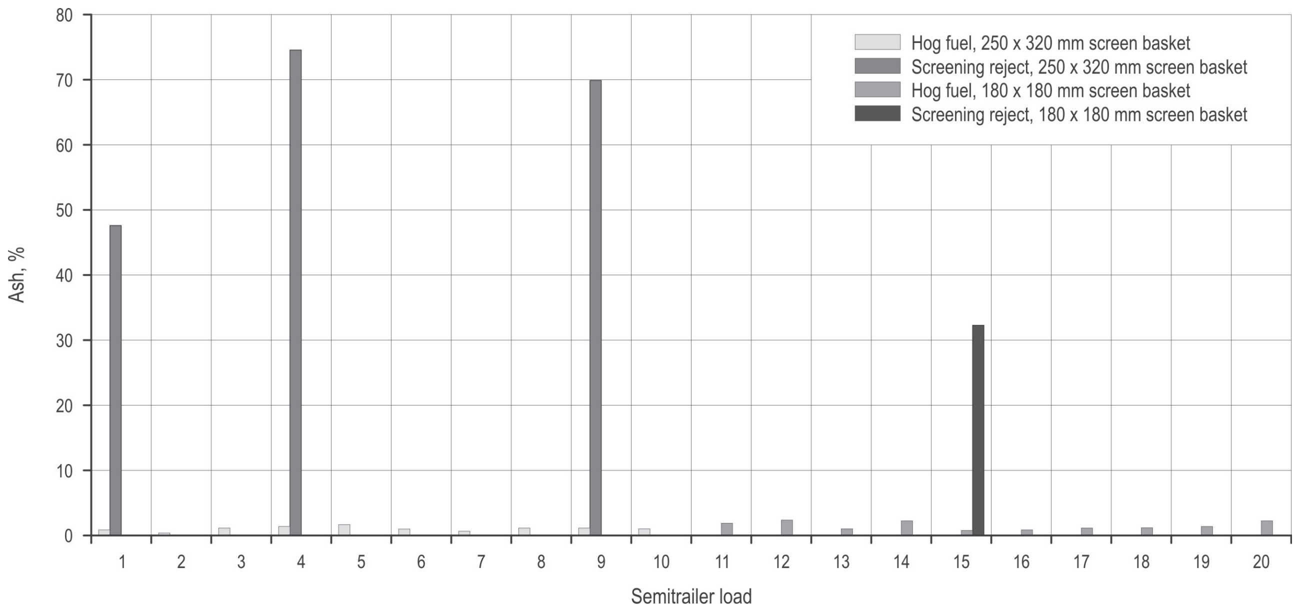

Fig. 7 Ash percentage of screening reject and hog fuel

Table 2 Properties of the screening reject

Sequence number of the load	Total volume of the screening reject, loose m^3	Total weight of the screening reject, kg	Moisture percentage of the screening reject, %t	Ash percentage of the screening reject, %t	Effective heating value of the screening reject, MJ/kg (dry mass)
1	4.5	1374	14.6	47.7	10.8
4	5.7	3094	18.4	74.7	5.2
9	7.5	3554	12.0	70.0	6.1
15	11.2	3310	22.3	32.4	13.4

When using the 250 x 320 mm screen basket, the in-feed loading was idled for, on average, 22% of the productive grinding time (min. 9% and max. 34%) during the time study.

3.2 Efficiency and quality of screening

The volume of screening reject varied in the range of 4.5–11.2 loose m^3 per studied semitrailer load (Fig. 6, Table 2), and thus, without screening, the payload of clean hog fuel would have been 78.8–85.5 loose m^3 (Fig. 6). Obviously, in practice, the impact of screening on the payloads is not so great, due to the heterogeneous blend of hog fuel and contaminants, and the smaller particle size of screening reject compared to hog fuel. The total weight of the screening reject per semitrailer load was in the range of 1374–3553 kg, and the moisture of the screening reject was 12–22% (Table 2). The ash content of the screening reject was 32.4–74.7%, and the effective heating value was 5.2–13.4 MJ/kg (Table 2). The effective heating value of the hog fuel was 17.9–19.9 MJ/kg (Table 3). The highest ash content and the lowest effective heating value and loose volume of the screening reject were found when using the 250 x 320 mm screen basket (Fig. 6 and Fig. 7, and Table 2).

The average ash content of the hog fuel was 1% (SD 0.36%) when using the 250 x 320 mm screen basket, and 1.5% (SD 0.61%) when using the 180 x 180 mm screen basket (Fig. 7, Table 3). The estimated ash content of the harvested stump wood was 3–6% before grinding and screening. The effective heating values of hog fuel for studied semitrailer loads 1, 4, 9, and 15 were, before screening, 14.8 MJ/kg, 11.9 MJ/kg, 13.6 MJ/kg, and 12.7 MJ/kg (wet basis), respectively, and screening improved heating values to 15.2 MJ/kg, 12.5 MJ/kg, 14.4 MJ/kg, and 13.1 MJ/kg (wet basis),

Table 3 Properties of the ground material per semitrailer load

Sequence number of the load	Ash percentage of the stump wood, %	Effective heating value of stump wood, MJ/kg (dry mass)	Payload of the semitrailer, m^3 (solid)	Solid content, %
1	0.85	19.0	–	–
2	0.36	18.9	–	–
3	1.14	17.9	–	–
4	1.37	19.3	–	–
5	1.64	19.0	–	–
6	0.96	19.9	–	–
7	0.62	18.7	–	–
8	1.13	19.6	–	–
9	1.14	19.2	–	–
10	1.02	19.2	–	–
11	1.88	18.9	21.8	24
12	2.34	18.4	24.3	27
13	1.02	19.1	21.7	24
14	2.21	18.9	21.2	24
15	0.75	19.1	24.7	27
16	0.82	19.1	22.8	25
17	1.11	19.0	–	–
18	1.18	19.5	–	–
19	1.38	19.9	–	–
20	2.23	19.5	–	–

respectively. The average payload of the semitrailer load was 22.8 m^3 (SD 1.45 m^3) and the average solid content was 25% (SD 1.6%) (Table 3). After grinding and screening, the majority of the hog fuel was in the particle size classes 63–100 mm and > 100 mm, and screening reject was in the particle size class < 3.15 mm (Fig. 8). When using the 180 x 180 mm screen basket, the relative share of bigger particles in the screening reject was higher compared to screening reject when using the 250 x 320 mm screen basket (Fig. 8).

3.3 Stack temperatures of the ground stump wood at the terminal buffer-storage

During the monitoring period of 64 days and 17 hours, the stack temperature of the ground stump wood at the terminal buffer storage fluctuated with the weather and season (Fig. 9), and rapid temperature increases caused by self-warming inside the stack were not observed. The highest temperatures observed inside the stack were 20°C at a 1 metre depth and 21°C at a 2 metre depth. At its lowest, the temperature was 0.5°C at a 1 metre depth, and 1°C at a 2 metre depth (Fig. 9).

4. Discussion and conclusions

Previous research on chippers and grinders comminuting woody biomass has highlighted the substantial increases in production rates that result from increasing the size of holes in the screens used (e.g. Kärhä et al. 2010a, Kärhä et al. 2011, Röser et al. 2012, Jylhä 2013), which supports the observations of this study. In addition, the fuel consumption has been noted to be higher when using narrower screens (Kärhä et al. 2010a, Kärhä et al. 2011, Jylhä 2013). In the study of Metsäteho (Kärhä et al. 2011), conifer stumps

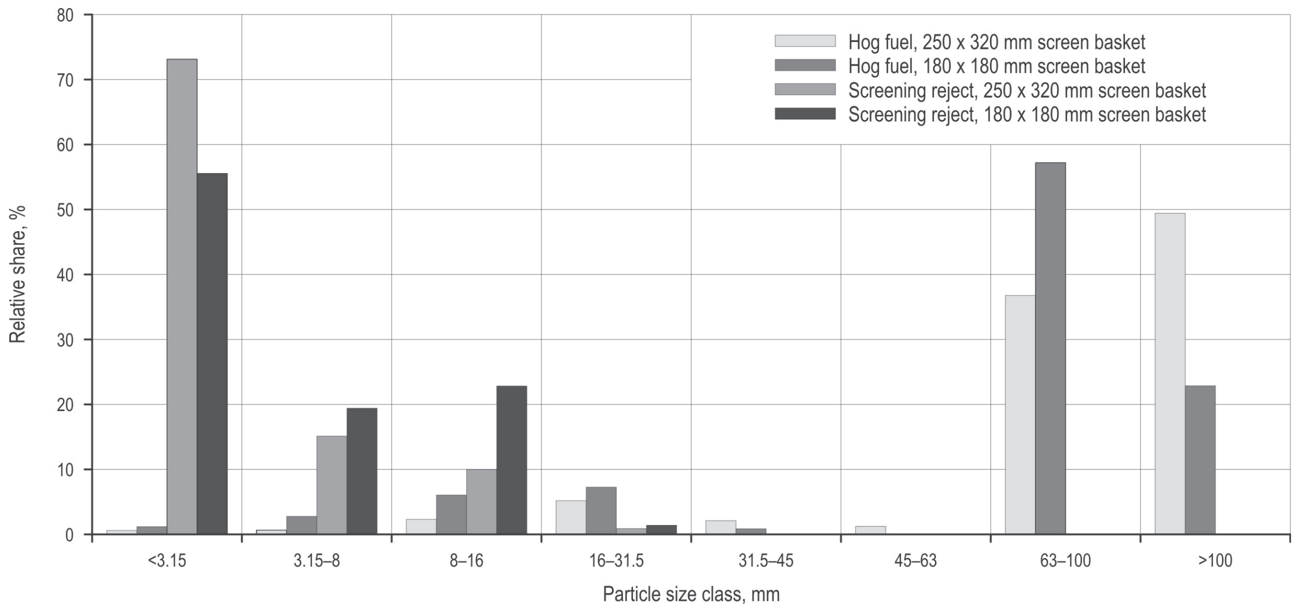

Fig. 8 Particle size distribution of screening reject and hog fuel when using the 250 x 320 mm and 180 x 180 mm screen baskets

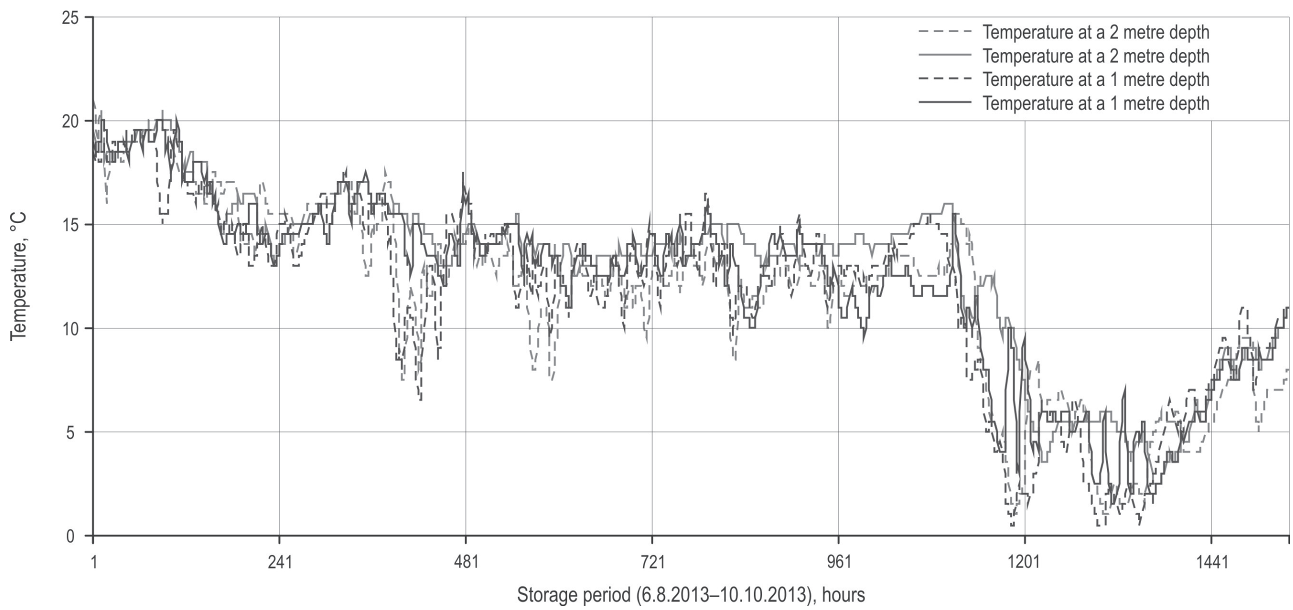

Fig. 9 Temperatures of ground stump wood (hog fuel) at a terminal stack at 1 and 2 meter depth

were pre-ground with a Crambo 5000 low-speed double shaft grinder using 500 x 320 mm and 120 x 90 mm screen baskets, and the grinding productivities were 171 loose m^3/E_0h with coarse screen, and 55 loose m^3/E_0h with a narrower screen. The fuel consumption of the grinder was 0.33 litres and 0.61 litres per loose m^3 (Kärhä et al. 2011).

In this study, the average ash content of hog fuel after screening was 1% when using the 250 x 320 mm screen basket, and 1.5% when using the 180 x 180 mm screen basket. However, the volumes of screening reject and wood losses were higher when using the narrower screen. The difference in the amount of screening reject was expected and visually so noticeable that one measurement was considered to be enough. The benefit of a narrower screen is that the productivity in the secondary grinding at the terminal or at the plant is higher compared to coarser hog fuel (Kärhä et al. 2011).

The weakness of the study reported herein was that the experimental setup was based on using a semitrailer with a 90 m^3 load volume as the base unit for productivity measurements and comparison of different treatments, because it was not possible to measure all loads with a certified weight scale. Therefore, the influence of the screen size on the solid content of hog fuel payloads was not examined. It is clear that dry mass is a more accurate unit compared to loose volume of hog fuel, but in recent studies in Finland, it has been noted that the variation in the solid content values of ground stump wood is unexpectedly narrow (Kärhä et al. 2011, Laitila et al. 2013).

In the study of Metsäteho (Kärhä et al. 2011), when using 500 x 320 mm and 120 x 90 mm screen baskets, the measured solid content of hog fuel payloads were 28% and 27%, respectively. In the study of Laitila et al. (2013), conifer stumps were ground with a CBI 5800 fast-running grinder using a 51/76 x 152 mm sieve, and the measured solid content of hog fuel payloads was on average 28% (SD 1.9%). In both studies, conifer stumps were ground at the roadside landings, loads were loaded with belt conveyers, and the technical properties of the ground stumps were similar to those reported in Table 1. However, for defining more accurate solid content of hog fuel loads and factors affecting that, more extensive follow-up and field studies should be conducted (cf. Uusvaara and Verkasalo 1987). Compared to whole trees or logging residue chips, the solid content of hog fuel payloads is about 10% lower (Uusvaara and Verkasalo 1987). In addition, the impact of contaminant content on the payload weights should be taken into account more carefully, because the weight of sand and rocks is significantly higher compared to stump wood.

During the time studies, both the grinder and the star screen were operating well, and there were no delays due to machine breakdowns. The mobile Crambo 6000 grinder was also capable of operating well in constricted roadside landings. The quality of the produced hog fuel was high, due to the low ash content, and this highlights the significance of screening to guarantee sufficient quality when processing stump fuel. The considerable variations in contamination levels result in widely varying concentrations of ash. For example, Anerud and Jirjis (2011) have reported ash content ranging between 2% and 7% for freshly ground stumps, and in the study by Laitila et al. (2013), the ash content of seasoned stumps was 13%. In the study by Korpinen et al. (2007), the ash content of the hog fuel samples varied from 1% to 24% and, for most samples, the ash content was below 10%.

In Sweden (Anerud 2012, von Hofsten et al. 2012, Fogdestam et al. 2012), studies were made on coarse grinding of stumps combined with sieving the ground stump wood. The contractor ground the stumps using a Doppstad DW 3060 low-speed grinder and the ground material was sieved using a Doppstad SM 620 drum sieve. The mesh size of the drum was 20 mm. An excavator and a truck-mounted grapple loader were used to load stumps into the grinder from the stump piles during the test.

In the first test, the grinder and sieve combination produced, on average, 17.7 dry tons of acceptable hog fuel per effective grinding hour, and the fuel consumption for the grinder was 2.8 litres per dry ton. During the sieving process, 22.3% of the ground material was rejected. This material had an ash content of 34%, while the accepted hog fuel had an ash content of 1.1% (Anerud 2012, von Hofsten et al. 2012). In the second test, the stumps were highly contaminated with soil and humus particles (ash content of 22%). Although, on average, 31% of the dry weight was rejected in the sieving process, the accepted material had an ash content of 7.6%, while the rejected material had an ash content of 53.9%. When grinding these stumps, the grinder produced 25.8 dry tons per effective hour, of which 18.7% was acceptable hog fuel after sieving. The average fuel consumption per acceptable dry matter ton was 1.75 litres for the grinder and 0.45 litres for the drum sieve (Anerud 2012, von Hofsten et al. 2012, Fogdestam et al. 2012).

In actual operations, the effect of delays or translocations reduces the productivity of the machinery and the whole supply chain in roadside landing operations. Therefore, readers must consider that the figures in this study refer to effective grinding time (E_0h) and were calculated for loading, grinding, and arrangements time only, excluding all delays and all other working time. In order to get representative data on delays in an operation, a long study period is needed, because delays or translocations can represent a significant proportion of chipper or grinder scheduled working time, and may account for up to 50% of the total site working time (Spinelli and Visser 2009, Eliasson et al. 2012, Holzleitner et al. 2013). Controlling the complex supply chain of chips from the forest to the customer is a complex task, and comminuting machines and truck-trailer units for transport must be scheduled with minimum operational delay to be profitable (e.g. Spinelli and Hartsough 2001, Stampfer and Kanzian 2006, Kanzian et al. 2009, Asikainen 2010, Holzleitner et al. 2013).

Self-warming inside the coarse ground stump wood stack was not observed during the two-month buffer-storage period, which is a benefit, because it is well known from previous studies that when comminuted biomass is stored, microbial activity will most likely take over. The first sign of this activity is heat generation (Kubler 1987, Nurmi 1990, Nurmi 1999, Jirjis 2005). The main reasons for the observed unresponsiveness of heat generation might be that the produced hog fuel was coarse, fines had been sieved away, wood material was dry, and buffer storage times were quite short. Jirjis (2005) pointed out that particle size has a strong impact on the storage properties of fuel chips, as it affects decay rate and durability: fines of less than 3 mm in length represent a health hazard because they reduce air circulation during storage, supporting bacteria proliferation with an increased risk of combustion. It is also known that chips made of fresh wood generate more heat and suffer greater dry material losses than if they are made of seasoned material (Björklund 1982, Kubler 1987).

The geometry of the procurement area, the main and forest road network density, the availability of forest fuels, and the end-use facility location relative to the procurement area affect transportation distances (Ranta 2002, Ranta 2005, Ranta and Rinne 2006, Laitila et al. 2010, Tahvanainen and Anttila 2011, Anttila et al. 2013). In future, the transportation distances, especially in coastal areas, will increase along with the growth of forest fuel consumption in Finland, and it is a question of transporting raw materials from surplus areas to deficit areas using transportation modes suitable for long-distance transportation (Ranta 2002, Ranta and Rinne 2006, Laitila et al. 2010, Tahvanainen and Anttila 2011, Anttila et al. 2013). In addition, centralised buffer storage is characteristic of these modes, which may be vital, especially for large-scale power plants (Ranta and Rinne 2006, Kanzian et al. 2009, Laitila et al. 2010). Therefore, methods with better transport economy, fuel quality, and storage properties, such as screened hog fuel, will obviously gain in competitiveness in the future. The produced parameters reported in this study are valuable information when developing novel supply systems for stump wood procurement.

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Authors' address:

Juha Laitila, PhD.*
e-mail: juha.laitila@luke.fi
Nuutinen Yrjö, PhD.
e-mail: yrjo.nuutinen@luke.fi
Natural Resources Institute Finland (Luke)
Yliopistokatu 6, FI–80101 Joensuu
FINLAND

* Corresponding author