Storage of Wood Chips: Effect of Chip Size on Storage Properties

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Abstract

To make forest biomass more competitive, increased efficiency in the handling and supply system is needed, thus producing high-quality fuel at a lower cost. Operating costs can be reduced if the target chip size is increased, as this increases productivity and reduces chipper fuel consumption. However, the chips need to be stored in order to meet fluctuating seasonal demand and maintain high machine utilisation. Due to biomass degradation, storage of comminuted biomass can lead to high energy losses, but can also increase fuel quality, e.g. by reducing moisture content and increasing net calorific value. This study evaluated the effects of storage on dry matter losses and differences in fuel quality of the stored biomass for three target chip sizes and three materials during six months of storage. The results showed that coarse chips had significantly lower moisture content and lower energy losses after storage than fine chips. Overall, changes during storage resulted in an economic loss of 3–4% per oven-dry ton for fine chips, but an economic gain of 2–6% for coarse chips. Thus increased target chip size can increase the competitiveness of forest biomass through decreased production costs and reduced storage costs. It can also ensure higher, more consistent fuel quality.

Keywords: storage, wood fuelchips, coarese wood chips, dry matter loss, fuel quality

1. Introduction

Storage of forest biomass to be used for heat and power is an inevitable step in all forest biomass supply systems due to irregular seasonal demand. Managing moisture is a key way to improve the net calorific value and cost-efficiency of energy wood supply, through the whole supply chain. In general, storage leads to lower moisture content and thus to higher net calorific value. The storage method and storage duration are essential for the result since woody biomass is easily rewetted and uneven demand for fuel leads to increased cost within the supply chain. The choice of storage location and storage method is usually influenced by economic and logistic considerations (Richardson et al. 2006). It is possible to reduce supply chain costs by more efficient utilisation of the equipment used in the supply chain throughout the year (Eriksson et al. 2017, Windisch et al. 2015, Väätäinen et al. 2017). However, this would lead to chipped material produced during the low-demand period being stored until the high-demand period. In Sweden, the greatest demand for wood fuel occurs during the cold season (November–February), when it is used to produce heat. Storage of chipped material would increase the ability to meet sudden increases in demand and would reduce the costs of maintaining winter roads, as woodchips would be stored at a terminal rather than at forest landings. Unfortunately, terminal storage adds handling and storage costs to the supply chain, which must be minimised to make it a viable option.

Forest fuels are generally considered to have variable fuel quality and fuel storage incurs risks of storage losses due to biological processes, as well as spontaneous fires in the stored material. Therefore, issues relating to feedstock quality changes and processes, leading to risks including extensive dry matter losses and self-ignition during storage, must be considered. Wood chips often heat up during storage, which can be attributed to microbial activity and chemical oxidation (Krigstin and Wetzel 2016). This heat development can, in some cases, lead to self-ignition of the stored biomass (Veznikova et al. 2014, Alakoski et al. 2016). In addition, microbial activity and oxidation can lead to dry matter losses and high energy losses from stored biomass (Jirjis 1995). These losses are usually higher during storage of wood chips than during storage of uncomminuted biomass, due to the increased surface area exposed to potential microbial degradation; in addition, there is reduced airflow and increased compaction.

Managing moisture content is a key issue since it affects both biological and chemical processes as well as the net calorific value. Using a semi-permeable material, which protects wood chips from rewetting while at the same time allows the release of water vapour and heat, is a partial solution (Anerud et al. 2018). Comminution allows to coarse wood chips, at least theoretically, increased airflow and less accumulated heat and, according to Baadgaard-Jensen (1988), the dry matter loss per month was much greater for wood chips (2.9%) than chunk wood (0.3%) during small-scale storage (Baadsgaard-Jensen 1988). This was verified by Pari et al. (2015), who reported accumulated dry matter losses of 12.9% from fine poplar wood chips and 7.2% from coarse poplar wood chips stored in 130 m^3 piles from March to June (Pari et al. 2015). Lenz et al. (2015) conducted a similar study on fine and coarse wood chips of poplar from short rotation coppice, where the chips were stored from January until November in 3.5 m high piles cowered with Toptex ® (Lenz et al. 2015). The cumulative losses after storage reached 22% from a pile built with fine chips (P31) and 21% from a pile built with coarse chips (P45) and there was no significant difference between the fractions. In Sweden, previous studies of wood chip storage examining the impact of fraction size on dry matter losses have generally been performed on small piles, often in the order of 10–50 m^3 (Björklund 1983, Thörnqvist 1983). Such piles are too small to be representative of storage at terminals in Sweden, where pile height is usually 5 to 7 m. However, since there are several studies that suggest that comminution to a larger average size of chips may have a positive effect on fuel quality, there is a real need to investigate fuel quality and amount of assessable energy under conditions encountered in real situations. Thus, one option is to increase the target chip size, which would enhance the storage properties of the chips and at the same time increase performance and reduce fuel consumption of chippers (Eliasson et al. 2015). However, increasing the target chip size will reduce but not eliminate the proportion of fines in the chips, and this proportion will continue to be fairly high for logging residue chips as an effect of the chipped material. Target chip size can be manipulated in two ways:

⇒ setting the cut length for the chipper, i.e. the distance between the drum/disc surface and the edge of the knife (Nati et al. 2010, Spinelli and Magagnotti 2012, Eliasson et al. 2012)

⇒ changing the mesh size in the bottom sieve or the distance between piece breakers (Eliasson et al. 2015, Nati et al. 2010).

While the first method changes the size of chips produced, the second method only reduces the amount of large/oversized chips. Chip size cannot be increased by increasing the mesh size in the sieve if it is already limited by the cut length. Furthermore, if machine utilisation is to be increased, it is important to study wood chip storage periods from summer to late autumn/early winter.

The aim of the present study was, thus, to evaluate the effect of type of biomass and wood chip particle size on changes in accessible energy and fuel quality properties during storage.

2. Material and Methods

2.1 Storage Location and Woody Material

The storage trial was established and initial sampling was performed in the first week of June 2013, within a terminal site at a combined heat and power (CHP) plant in Östersund (63°12′N; 14°39′E). The materials were stored until 5 January 2014, when the trial ended.

Three types of biomass chips were tested in the study, chips from:

⇒ recently harvested tree sections

⇒ pre-stored forest residues

⇒ pre-stored stemwood.

The tree sections consisted of a mix of pine (*Pinus* spp.), spruce (*Picea abies*), aspen (*Populus* spp.) and birch (*Betula* spp.) harvested during thinning in an area close to Åre Östersund Airport during May 2013 (cf. (Eliasson et al. 2015)). The forest residues and stemwood were harvested in 2012, delivered to the CHP plant in Östersund during 2012–2013 and stored there without cover. Both materials were dominated by Norway spruce (*Picea abies* (L.) H. Karst). Immediately prior to the experiment, tree sections were chipped at the landing, while residues and stemwood were chipped at the CHP terminal.

Chipping was performed using two tractor-powered drum chippers, a Kesla C645 and a Eschelboeck Biber 92. Three different bottom sieves were used in the chippers to produce different types of chips: coarse using 100 mm mesh, medium using 50 mm mesh and fine using 25 mm (Kesla) or 35 mm (Biber) mesh. For logging residues and stemwood, the Kesla chipper was used to produce all medium and coarse chips, while the Eschelboeck was used to produce all fine

Table 1 Results of analysis of variance (ANOVA) on wood chip size distribution data

Effect	Num *DF*	Den *DF*	*F* Value	*Pr* > *F*
Sieve	2	216	0.00	0.9999
Material	2	216	0.00	1.0000
Sieve * Material	4	216	0.00	1.0000
Size class	7	216	31.45	<.0001
Sieve * Size class	14	216	9.12	<.0001
Material * Size class	14	216	4.62	<.0001
Sieve * Material * Size class	26	216	1.77	0.0154

chips; for the tree sections a comparative trial of the chippers were made (Eliasson et al. 2015), where both chippers produced all types of chips. However, no effect of chipper type on chip size distribution was found (Eliasson et al. 2015). In addition, a batch of coarse tree section chips was sieved using a drum sieve to remove fine fractions prior to storage. Tests of differences in chip size distribution produced by the different sieves and materials were carried out as in (Eliasson et al. 2015), using the GLIMMIX procedure in SAS. Even though the bottom sieve in a chipper is not the main factor affecting chip size (Eliasson et al. 2015), there were significant differences in particle size distribution between the chips depending on material and sieve used (Table 1).

The effects within each material (Fig. 1) were as follows:

⇒ Tree sections: The coarse sieve produced significantly fewer chips in the 3–8 mm class and more in the 31–45 mm class than the fine and medium sieves. Chips produced with the coarse sieve and sieved using a drum sieve contained significantly fewer 3–8 mm chips than other chip types

⇒ Forest residues: The fine sieve produced significantly smaller chips than the other sieves. The coarse sieve produced more oversized chips (>100 mm) than the other sieves

⇒ Stemwood: The fine sieve produced significantly smaller chips than the other two sieves.

2.2 Weather Conditions During Storage

Historical data (30-year averages) on local weather conditions, based on values for Östersund, were obtained from the Swedish Meteorological and Hydrological Institute (SMHI). These data were used for

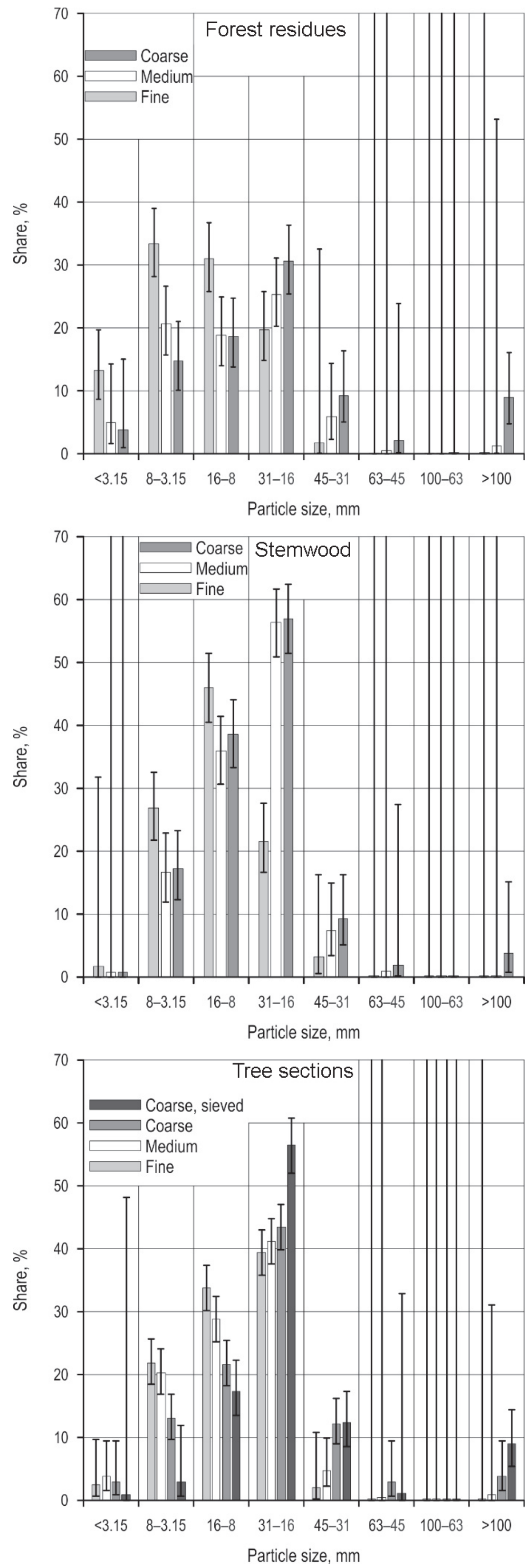

Fig. 1 Particle size distribution and classification of wood chips used in the study

comparison with measured data during the experiments, allowing the results to be set in a historical context. The ambient temperature during chipping, homogenisation and pile construction was 16 °C, which was only marginally different from the average long-term value according to data from SMHI. Total precipitation during the study period was 305.2 mm, which was not different from the 30-year average value (306 mm), and 25.3 mm of this precipitation fell when the ambient temperature was below 0 °C. Four heavy rainfall events (>15 mm/day) occurred during the storage period, on 30 July, 31 August and 16 and 17 September.

2.3 Study Design, Sampling and Analyses

The chips were stacked in 5 m high windrows, within which each material was placed in approximately 6–7 m wide separate sections. One windrow was made using the freshly harvested material and one with the pre-stored material. The windrows were of similar width (11 m), while the base length differed (35 and 45 m, respectively) (Fig. 2). The estimated volume of the windrows of fresh and pre-stored biomass was 825 m^3 and 1100 m^3, respectively. The windrows were constructed on a paved area at the terminal with their long axis positioned north-west/south-east, perpendicular to the prevailing wind direction.

Each vertical section of the windrows (see Fig. 2) contained seven sampling points located at three heights:1.5 m, 3.0 m and 4.5 m (see Fig. 3).

During windrow construction, six samples were collected at each of these sampling points. Half the sample material was retained for further analysis of initial characteristics of wood chips, while the other half was divided into net bags, weighed and placed back in the pile, to determine how its quality changed during storage. Temperature changes at 3 m in the middle of the windrows were measured at a sampling frequency of 30 min in each section, using one Tinytag® temperature logger (marked »T« in Fig. 3). The sampling procedure, sample preparation and all analyses were performed according to European standard methods (Table 2).

The initial dry weight of the samples in the net bags was used as the basis for the calculation of dry matter losses, which were expressed as a weight percentage on a dry matter basis. Finally, energy recovered was calculated as follows:

$$E_{recovered} = \left(\frac{DM * (1 - 0.01 * DML)}{1 - 0.01 * M} \right) + Q \qquad (1)$$

Where:

$E_{recovered}$ energy
DM dry matter
DML dry matter lost
M moisture content
Q net calorific value.

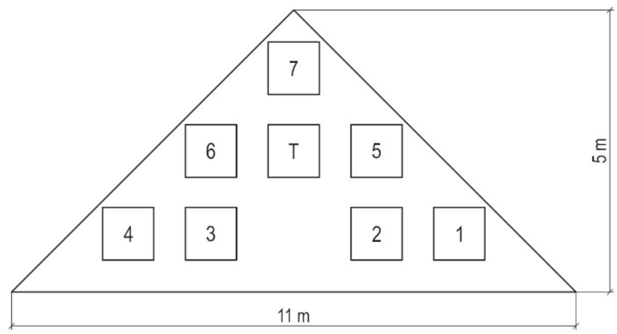

Fig. 3 Cross-section of an experimental windrow showing sampling points and location of temperature sensors (T) in each section

Table 2 Standard methods used for sampling, sampling preparation and determination of fuel quality parameters

Analysis	Standard method
Sampling	SS-EN 14778 (Anon. 2011c)
Sample preparation	SS-EN 14780 (Anon. 2011b)
Determination of moisture content	SS-EN 14774 (Anon. 2009b)
Determination of ash content	SS-EN 14775 (Anon. 2009a)
Determination of calorific value	SS-EN 14918 (Anon. 2010a)
Conversion of analytical results from one base to another	SS-EN 15296 (Anon. 2011a)
Determination of particle size distribution	SS-EN 15149 (Anon. 2010b)

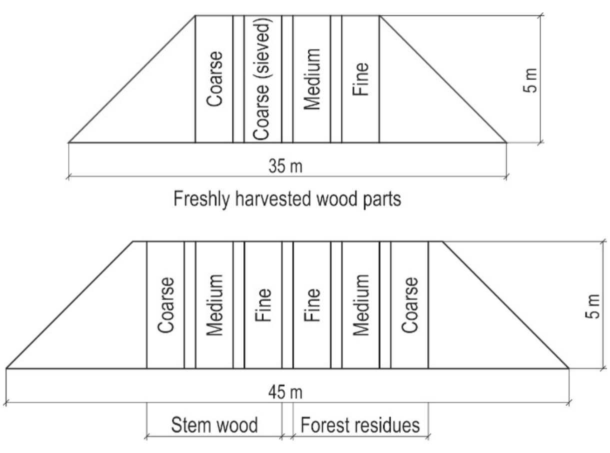

Fig. 2 Side view of experimental windrows showing sections containing wood chips of different origin and sizes

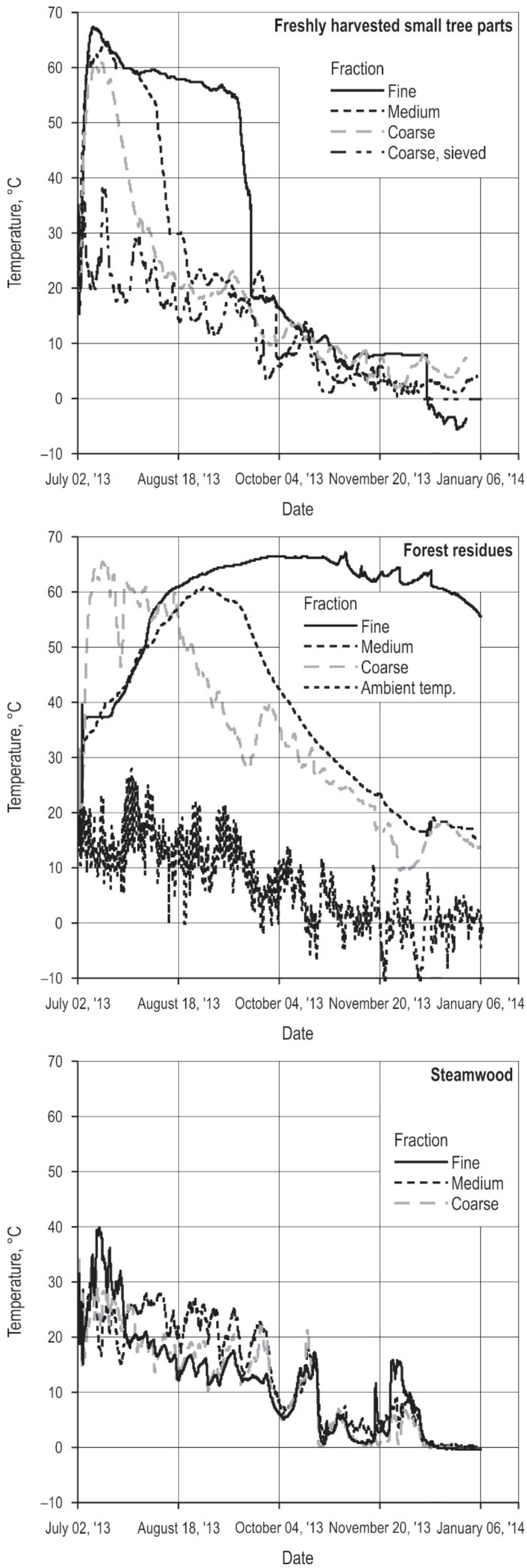

Fig. 4 Ambient temperature and temperature changes within windrow sections containing wood chips

2.4 Statistical Analyses

The experiment was treated as a complete randomised factorial experiment. The assumption of homogeneity of variances between fraction class within each assortment was tested using Levene's test. For the statistical analyses, the general linear model (GLM) was used for analysis of variance (ANOVA), followed by Tukey's *HSD* test. The data obtained for five variables (moisture content, dry matter loss, ash content, calorific value and recovered energy) were analysed with regard to the factors fraction class, material and, in some cases, position. All analyses were performed in STATISTICA v.10 and differences between factors and their interactions were considered significant at $p<0.05$.

3. Results

3.1 Temperature Changes within Windrows

In general, the temperature rapidly increased to above 60 °C, irrespective of chip size class, in windrow sections containing freshly harvested tree sections (Fig. 4). Similar, but slightly slower, increases were observed for chips produced from forest residues, in particular for the temperature rise from 35 °C onwards. The temperature change was more moderate for stemwood chips and sieved coarse chips from freshly harvested tree sections. The highest temperatures were observed for fine chips, followed by medium and coarse chips. Moreover, the high temperature was maintained for longer when freshly harvested tree sections were chipped to the smaller size, while for forest residues there was no clear trend. For forest residues, the temperature at the end of the storage period was still higher than the ambient temperature, whilst the temperature in the windrow sections made with freshly harvested tree sections and stemwood was roughly similar to the ambient temperature.

3.2 Moisture Content

No differences in initial moisture content between fractions within unsieved tree-sections and stemwood could be established (Table 3). In contrast, there was a significant difference in initial moisture content in medium chips (28.9%) compared to the average value (39.7%) for fine and coarse chips. The sieved coarse fraction produced from tree-sections was slightly drier compared to the unsieved biomass. The average moisture content in windrows built with coarse chips from tree sections, forest residues and stemwood chips decreased after storage, while moisture content in

Table 3 Mean moisture content (%, wet weight basis) and 95% level of confidence (in brackets). Different letters within columns indicate significant differences between size fractions within biomass type and different Greek letters indicate significant differences within row and material

	Tree sections		Forest residues		Stemwood chips	
	July	January	July	January	July	January
Fine chips	$42.1^{a\alpha\beta}$ (0.6)	$38.6^{a\alpha\beta}$ (4.1)	$40.7^{a\alpha\beta}$ (1.4)	$44.6^{a\beta}$ (3.6)	$37.2^{a\alpha}$ (0.7)	$39.7^{a\alpha\beta}$ (5.9)
Medium chips	$41.7^{a\alpha}$ (0.7)	$37.3^{a\beta}$ (3.2)	$28.9^{b\gamma}$ (1.1)	$26.4^{b\gamma}$ (4.0)	$37.3^{a\beta}$ (0.5)	$36.0^{a\beta}$ (3.7)
Coarse chips	$42.7^{a\alpha}$ (1.2)	$30.8^{b\beta}$ (2.5)	$38.7^{a\gamma}$ (0.9)	$25.6^{b\beta}$ (3.4)	$38.1^{a\gamma}$ (0.8)	$32.2^{a\beta}$ (2.9)
Sieved coarse chips	$39.9^{b\alpha}$ (1.1)	$33.3^{ab\beta}$ (2.8)	–	–	–	–

Table 4 Mean gross calorific value (MJ kg^{-1}, dry weight basis) and 95% level of confidence (in brackets). Different letters within columns indicate significant differences between size fractions within biomass type and different Greek letters indicate significant differences within row and material

	Tree sections		Forest residues		Stem wood chips	
	June	January	June	January	June	January
Fine chips	$20.47^{a\alpha}$ (0.12)	$20.90^{a\beta}$ (0.24)	$20.41^{a\alpha}$ (0.09)	$21.92^{a\gamma}$ (0.10)	$20.60^{a\alpha}$ (0.09)	$21.20^{a\varepsilon}$ (0.09)
Medium chips	$20.33^{a\alpha}$ (0.08)	$21.40^{b\beta\gamma}$ (0.23)	$20.15^{b\alpha}$ (0.14)	$21,29^{b\beta\delta}$ (0.10)	$20.59^{a\gamma}$ (0.08)	$21.12^{a\delta}$ (0.08)
Coarse chips	$20.42^{a\alpha}$ (0.08)	$21.90^{c\beta}$ (0.24)	$20.20^{b\gamma}$ (0.10)	$21.79^{b\beta}$ (0.10)	$20.66^{a\delta}$ (0.09)	$21.06^{a\varepsilon}$ (0.06)
Sieved coarse chips	$20.58^{b\alpha}$ (0.05)	$21.02^{ab\beta}$ (0.20)	–	–	–	–

stored fine chips produced from forest residues and stemwood increased (Table 3). The change in moisture content was greatest in windrow sections built with material from fresh tree sections and lowest in those built with stemwood chips. The tops and sides of the windrows were clearly rewetted and consequently, the main reduction in moisture content was found at levels below 3 m. All windrow sections exhibited a significant (p<0.05, R^2=0.72) negative correlation between change in moisture content during storage and vertical position within the pile. The rewetting in the top and middle layer was especially pronounced for fine fractions, irrespective of the material used.

3.3 Ash Content

The initial ash content in chips produced from freshly harvested tree sections was 2.2% for unsieved and 1.8% for sieved chips. The difference between these groups was significant (p<0.05). The ash content of chips produced from forest residues was 3.8% when chipped to coarse and fine sizes, and 6% when chipped to medium size. This is an effect of large variability in quality for the stored residues prior to chipping. Chips produced from stemwood were very homogeneous and had an ash content of 1.1%. In general, the ash content in windrow sections produced from the tree sections and forest residue materials increased by 0.3% after six months of storage. No such change was observed in chip piles produced from stemwood. The change in ash content determined after storage was significantly (p<0.05) positively correlated with vertical pile position (R^2=0.47).

3.4 Gross Calorific Value

Initial gross calorific value ($q_{\mathrm{Vgr,d,}}$) was correlated to initial ash content (R^2=0.32). In general, the gross calorific value increased significantly in all treatments during storage (Table 4). No correlation (R^2=0.01, p=0.39) was found between initial gross calorific value and gross calorific value after storage.

3.5 Dry Matter Losses

The coarse fraction produced from tree sections showed an average loss of 4.1%, while the average loss from the sieved coarse fraction was 2.8%. The average dry matter loss of fine and medium size chips was 6.6%. The average loss of dry matter within the windrow sections built with coarse and medium chips produced from forest residues was 4.8%, while it reached 10.9% in the windrow section containing fine chips. For stemwood, the average dry matter loss of coarse chips was 1.4%, while for fine and medium-sized chips it was 3.4%. In general, all types of biomass showed a positive correlation between moisture content and dry matter losses. Fresh biomass and chips from tree sections and forest residues showed a significant (p<0.05, R^2=0.60) positive correlation between moisture content and dry matter loss. In addition, there was generally a significant (p<0.05, R^2=0.70) negative correlation between particle size and dry matter losses when only coarse and fine fractions were included.

3.6 Energy Change

The average amount of accessible energy expressed as Q, derived from 1 kg dry weight of coarse chips

Table 5 Mean amount of accessible energy (MJ) derived from 1 kg initial dry material and 95% level of confidence (in brackets). Different letters within columns indicate significant differences between size fractions within biomass type and different Greek letters indicate significant differences within row and material

	Tree sections		Forest residues		Stem wood chips	
	July	January	July	January	July	January
Fine chips	$17.38^{a\alpha}$ (0.12)	$16.64^{a\beta}$ (0.47)	$17.41^{a\alpha}$ (0.13)	$16.54^{a\beta}$ (0.48)	$17.85^{a\gamma}$ (0.11)	$17.24^{a\alpha\beta}$ (0.67)
Medium chips	$17.27^{a\alpha}$ (0.11)	$17.43^{b\alpha}$ (0.23)	$17.85^{b\beta}$ (0.14)	$18.23^{b\beta}$ (0.39)	$17.83^{a\beta}$ (0.08)	$17.80^{ab\beta}$ (0.36)
Coarse chips	$17.50^{ab\alpha}$ (0.09)	$18.68^{c\beta}$ (0.31)	$17.34^{a\alpha}$ (0.13)	$17.99^{b\gamma\delta}$ (0.36)	$17.85^{a\gamma}$ (0.10)	$18.22^{b\delta}$ (0.21)
Sieved coarse chips	$17.64^{b\alpha}$ (0.09)	$17.87^{b\alpha}$ (0.25)	–	–	–	–

increased when the chips were produced from freshly harvested tree sections and forest residues (Table 5). The change in recoverable energy was higher for coarse fractions than for fine fractions and the amount of accessible energy was significantly positively correlated (R^2=0.32) with fraction class.

Assuming an energy price of 18.2 € per MWh, the energy changes observed were equivalent to an economic loss during storage of 3.1 € and 3.7 € per oven-dry ton (–3–4%) for fine chips from roundwood and tree sections, respectively, while the value of the stored coarse chips actually increased by 6.0 and 1.8 € per oven-dry ton (+6–2%), respectively. Similar differences between fine and coarse chips were seen for logging residues, but with larger losses during storage.

4. Discussion

The temperature change within a windrow of wood chips is influenced by a variety of factors in addition to particle size; these include material composition, initial moisture content and degree of compaction. This has been reported in numerous studies and the processes are well documented (Krigstin and Wetzel 2016). Three different forest biomass types (tree sections, forest residues, stemwood) were used as raw material for the different sizes of chips (fine, medium, coarse) produced in this study. Forest residues were the most heterogeneous material, and staff at the CHP moved and restacked these residues on arrival at the terminal, so the material from which the chips were produced may have come from very different sources, a fact reflected mainly in the initial moisture content.

We aimed to homogenise each forest biomass type before windrow construction and, in general, the initial values determined for the fuel quality parameters were similar, with minor variations; this was the case for all except the medium-sized chips produced from forest residues. Windrow height and size were factors that were found to be positively correlated with temperature changes within the material, confirming earlier reports (Thörnqvist 1985). The height of the windrows (5 m) was a little low, but within the range of what is used in practice in Sweden, which means that the ratio between the surface area and volume was higher, i.e. precipitation per m^3 stored fuel was higher than in commercial situations. Nevertheless, the height was significantly greater than in studies examining poplar, and the size of the pile as well as the storage period were adopted to reflect working conditions in Sweden. The temperature within the windrows was low and the difference in temperature change between different fractions was most obvious in windrow sections built with freshly harvested tree sections from thinning operations, indicating a difference in dry matter losses.

The change between the initial and final moisture content was greatest for the coarse chips and the lowest average moisture content was found for freshly harvested tree sections. A previous study found that fine poplar wood chips dried to a moisture content of 34% when stored in a 3.5 m high pile, while coarse chips dried to a moisture content of 29% under similar conditions (Lenz et al. 2015). However, another study found that fine chips of poplar dried to a moisture content of 26.4% and coarse chips to a moisture content of 34.4% during a period of 120 days (Pari et al. 2015). The difference between those studies could be because of different amounts of precipitation during the storage period, different lengths of storage period and differences in climate between study sites. Variations in moisture content within the windrow sections in the present study increased markedly over time and were especially pronounced as the top and edges of the windrow were clearly rewetted through a combination of condensation of water vapour from within the windrow and external precipitation. This redistribution of moisture was in agreement with published findings for similar biomass stored in small piles (Thörnqvist 1983). Moist areas of the windrows, in which the highest dry matter losses were determined, were visibly more infected by microorganisms such as moulds, an effect that can mainly be attributed to a more favourable environment for biodegrading microorganisms.

In addition to moisture, the composition of the biomass had a decisive impact on the magnitude of dry matter losses. Forest residues and small tree chips had a higher proportion of bark and needles, which resulted in higher concentrations of easily accessible nitrogen and easily soluble carbohydrates, favouring microbial growth. It was obvious that fine chips were wetter, more infected with moulds and more compact than coarse chips.

The slight increase observed in ash content and clear negative correlation between ash content and height within the windrow could be related to dry matter losses. Variations in initial gross calorific value (*q*Vgr, d) before and after storage were related to changes in ash content, but in particular to dry matter losses. Windrow sections built with fine chips consistently lost more biomass than those built with coarse chips. In general, the dry matter losses observed for tree sections and forest residues (6.6–10.9% from fine chips, 2.8–4.8% from coarse) were comparable to those reported during storage of poplar wood chips in Italy (12.9% from fine chips and 7.2% from coarse after storage for 120 days) (Pari et al. 2015). However, dry matter losses from chips produced from pre-stored stemwood (1.4–3.4%) were much lower than those reported in the literature (22% from fine chips and 21% from coarse chips after 9 months of storage) (Lenz et al., 2015).

It is common for the energy change in stored biomass to be equated to the change in net calorific value (*Q*) on a dry matter basis (*q*p, net, d). However, this type of comparison does not reflect the whole picture. A more accurate comparison is the difference in *Q* based on initial dry weight, including both dry matter losses and changes in moisture content. The total amount of available energy in the coarse chips increased due to a combination of drying and low dry matter losses, while the energy in the other size fractions remained at the same level throughout.

Producing fine chips is both less productive and more fuel-consuming than producing coarse chips (Eliasson et al. 2015), and thus production costs are substantially higher. When the better storability of the coarser chips is added, the production costs may be even lower for this fraction, as the lack of storage losses enables increased chipper utilisation during the year, thus decreasing fixed machine costs per ton of chips produced. Terminal storage of chips will lead to costs for handling the chips, i.e. stacking, reloading and transport (especially if the terminal is not adjacent to the heating plant). However, if the losses during storage can be minimised or, as in this study, if the accessible energy value increases, reduced chipping and transport costs may cover the storage costs. For chipping and transport contractors, increased annual chipper utilisation that is fairly uniform between months would improve planning and give a more predictable cash flow. Furthermore, it would be easier to find and retain chipper operators and chip truck drivers, as the work would change from being seasonal to year-round. It is likely that comminution to a coarse fraction, combined with sieving and covering the stored chips, can result in less degradation and more accessible energy after storage since a breathable cover protects the biomass from rewetting and leads to lower losses (Anerud et al. 2018). However, the cost of this combination has to be assessed in future studies.

5. Conclusions

Coarse wood chips were found to have several advantages from a storage perspective: better drying, lower dry matter losses, higher net calorific value and more available energy. These benefits, in combination with advantages arising during chipping of increased productivity and decreased chipper fuel consumption, indicate that production of larger chips containing a low proportion of fines might be a feasible way to reduce production costs and storage losses. This could increase the competitiveness of forest fuels if customers are willing to accept a slightly larger proportion of large chips. Further studies are needed to evaluate whether additional sieving of the chips to further reduce the proportion of fines can be achieved in an economically feasible way.

6. References

Alakoski, E., Jämsén, M., Agar, D., Tampio, E., Wihersaari, M., 2016: From wood pellets to wood chips, risks of degradation and emissions from the storage of woody biomass – A short review. Renewable and Sustainable Energy Reviews 54: 376–383: https://doi.org/10.1016/j.rser.2015.10.021

Anerud, E., Jirjis, R., Larsson, G., Eliasson, L., 2018: Fuel quality of stored wood chips – Influence of semi-permeable covering material. Applied Energy 231: 628–634. https://doi.org/10.1016/j.apenergy.2018.09.157

Anon. 2009a: Solid biofuels – Determination of ash content. SS-EN 14775. Swedish standards institute.

Anon. 2009b: Solid biofuels – Determination of moisture content – Oven dry method – Part 1: Total moisture – Reference method. SS-EN 14774. Swedish standards institute.

Anon. 2010a: Solid Biofuels – Determination of calorific value. SS-EN 14918. Swedish standards institute. Solid Biofuels.

Anon. 2010b: Solid biofuels – Determination of particle size distribution – Part 1: Oscillating screen method using sieve apertures of 1 mm and above SS-EN 15149-1:2010. Swedish Standard Institute.

Anon. 2011a: Solid biofuels – Conversion of analytical results from one basis to another. SS-EN 15296. Swedish standards institute.

Anon. 2011b: Solid biofuels – Sample preparation. SS-EN 14780. Swedish standards institute.

Anon. 2011c: Solid biofuels – Sampling SS-EN 14778. Swedish standards institute.

Baadsgaard-Jensen, J., 1988: Storage and energy economy of chunk and chip piles. Research Report-Exploitation of Marginal Forest Resources for Fuel.

Björklund, L., 1983: Lagring av helträdsflis av olika trädslag samt i olika fraktioner. Sveriges lantbruksuniversitet, Institutionen för virkeslära.

Eliasson, L., Granlund, P., Johannesson, T., Von Hofsten, H., Lundström, H., 2012: Flisstorlekens effekt på en stor skivhuggs bränsleförbrukning och prestation. Arbetsrapport Från Skogforsk, 10 p.

Eliasson, L., Von Hofsten, H., Johannesson, T., Spinelli, R., Thierfelder, T., 2015: Effects of sieve size on chipper productivity, fuel consumption and chip size distribution for open drum chippers. Croatian Journal of Forest Engineering: 36(1): 11–17.

Eriksson, A., Eliasson, L., Sikanen, L., Hansson, P.-A., Jirjis, R., 2017: Evaluation of delivery strategies for forest fuels applying a model for Weather-driven Analysis of Forest Fuel Systems (WAFFS). Applied Energy 188: 420–430. https://doi.org/10.1016/j.apenergy.2016.12.018

Jirjis, R., 1995: Storage and drying of wood fuel. Biomass and Bioenergy 9(1–5): 181–190. https://doi.org/10.1016/0961-9534(95)00090-9

Krigstin, S., Wetzel, S., 2016: A review of mechanisms responsible for changes to stored woody biomass fuels. Fuel 175: 75–86. https://doi.org/10.1016/j.fuel.2016.02.014

Lenz, H., Idler, C., Hartung, E., Pecenka, R., 2015: Open-air storage of fine and coarse wood chips of poplar from short rotation coppice in covered piles. Biomass and Bioenergy 83: 269–277. https://doi.org/10.1016/j.biombioe.2015.09.018

Nati, C., Spinelli, R., Fabbri, P., 2010: Wood chips size distribution in relation to blade wear and screen use. Biomass and Bioenergy 34(5): 583–587. https://doi.org/10.1016/j.biombioe.2010.01.005

Pari, L., Brambilla, M., Bisaglia, C., Del Giudice, A., Croce, S., Salerno, M., Gallucci, F., 2015: Poplar wood chip storage: Effect of particle size and breathable covering on drying dynamics and biofuel quality. Biomass and Bioenergy 81: 282–287. https://doi.org/10.1016/j.biombioe.2015.07.001

Richardson, J., Björheden, R., Hakkila, P., Lowe, A., Smith, C., 2006: Bioenergy from sustainable forestry: guiding principles and practice. Springer Science & Business Media.

Spinelli, R., Magagnotti, N., 2012: The effect of raw material, cut length, and chip discharge on the performance of an industrial chipper. Forest products journal 62(7–8): 584–589. https://doi.org/10.13073/FPJ-D-12-00083.1

Thörnqvist, T., 1983: Storing of disintegrated logging residuals. Rapport-Sveriges Lantbruksuniversitet, Institutionen för Virkeslära (Sweden).

Thörnqvist, T., 1985: Storing of forest residues and comminuted fuels from forest residues. Storing of forest residues and comminuted fuels from forest residues 153: 3 p.

Veznikova, H., Perdochova, M., Bernatík, A., Binkau, B., 2014: Safe storage of selected fuels with regard to their tendency to spontaneous combustion. Journal of Loss Prevention in the Process Industries 29: 295–299. https://doi.org/10.1016/j.jlp.2014.03.011

Windisch, J., Väätäinen, K., Anttila, P., Nivala, M., Laitila, J., Asikainen, A., Sikanen, L., 2015: Discrete-event simulation of an information-based raw material allocation process for increasing the efficiency of an energy wood supply chain. Applied energy 149: 315–325. https://doi.org/10.1016/j.apenergy.2015.03.122

Väätäinen, K., Prinz, R., Malinen, J., Laitila, J., Sikanen, L., 2017: Alternative operation models for using a feed-in terminal as a part of the forest chip supply system for a CHP plant. Gcb Bioenergy 9(11): 1657–1673. https://doi.org/10.1111/gcbb.12463

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