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Influence of storage on properties of wood chip material

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Abstract

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The use of bioenergy for district heating is usually seasonal with a high consumption during the cold periods. Therefore some type of the harvested material storage is necessary. Woody materials are usually reduced in size to chips and stored outdoors in piles or under cover. During storage the materials decompose as a result of chemical and biological processes resulting in dry matter loss. The degree and rate of decomposition primarily depend on material moisture content and temperature. In this study four piles of wood chips, each containing 240 t wet weight, were studied for moisture content and temperature development during 5.5 months of storage. Two piles were stacked normally and two compacted at 50 to 60 kPa pressures. Additionally, a ventilating tarp, TopTex, was used to test the effect of covering the material. Nylon net bags with the same chip material were placed at different positions in the piles for moisture content determination. The volume of three piles shrunk between 3 and 6% but the volume of the uncovered compacted pile shrunk almost 6%. The low shrinkage indicated that material losses in this study were small. The temperature development in all piles followed a similar pattern but with maximum temperatures at different positions, top for the uncompacted pile and innermost for the compacted one. The ventilation tarp on the piles had only a minor effect on the temperature development. Moisture content decreased but the results are uncertain due to problems with the scale precision. Net bag analyses showed that the lowest moisture loss occurred in the middle of the uncovered compacted pile but the values only refer to their specific position in the pile.

Keywords: energy; measurements of moisture

The use of bioenergy for district heating is usually seasonal with a heavy consumption during the cold periods. In Nordic conditions the harvesting of biomass such as logging residues, stumps and small stems usually occurs during the extended summer season.

During the winter with deep snow cover, it is difficult to transport the biomass to deposit areas or to the sides of forest roads. Some type of storage is therefore necessary. Most often the district heating plants have limited or too few storage areas for the storage of material. Usually the biomass is stored uncompacted to avoid loss and this demands lots of storage areas. Thus, the district heating plants must have the capacity to comminute the material before use.

During wood chip storage both substance and energy are lost due to material break down with the production of carbon dioxide, water and heat (Zabel, Morrell 1992). There are several studies showing that 2–4% of the woody substance is lost per month in storage outdoors (Thörnqvist 1982; Jirjis et al. 2008; Afzal et al. 2010). Wood resins and hemicelluloses are lost during the first months of storage (Back, Allen 2000; Richardson et al. 2002; Mohan et al. 2006). Typical values are around 1.5–3 wt% per month (Greaves 1975; Fuller 1985). Although the energy content of lipids and wood resins is high (Kossuth et al. 1982, 1984), their low concentrations in woody material mean that the energy loss is almost negligible.

According to Nylinder and Thörnqvist (1980), Thörnqvist (1982), and Barontini et al. (2014) chopped softwood and hardwood material loses about 20–24% of its mass and 15–19% of its effective heating value after 3–6 months of storage. The share of fines (< 7 mm) does not have much influence on the losses, whereas the type of material (softwood or hardwood) could have a large influence (Lehtikangas 1999). Furthermore, the initial moisture content of the material and its changes during storage are of importance. Thörnqvist (1982) found that moisture content in piles of chipped material decreased considerably in the centre of the pile (down to 25%) whereas in the upper and outer parts it could increase to 65–70 wt% compared to the initial moisture content.

The heat produced in wood decomposition causes the air in the pile to move upwards (Zabel, Morell 1992). When the warm and humid air reaches the surface of the pile, it is cooled down and moisture condenses on the surface (Thörnqvist 1982). To protect the chip pile from moisture precipitation and in order to increase ventilation, Thörnqvist (1982) tested a roof cover for the pile and showed that the loss of moisture of the pile using that method was reduced by half compared to the uncovered pile.

The amount of accumulated heat in a pile depends on the ventilation. Small piles (< 100 m^3) with coarse material or uncomminuted material have a high pore volume and are therefore easy to ventilate and there is seldom a risk for self-heating (Thörnqvist 1985).

At comminution of the material the amount of exposed wood surface increases considerably. In large piles the temperature starts to increase directly after piling and within a few days the inner part of the pile reaches a temperature where only thermophilic microorganisms can survive (Lehtikangas 1999; Barontini et al. 2014).

The heated air in the pile transports moisture to the surface and thus the inner parts dry out. To dry out a pile the ventilation must be good and this can be accomplished with a cone-shaped pile. However, the pile should not be higher than 7 m, otherwise the heat development inside the pile becomes too high and self-ignition might occur (Lehtikangas 1999). The use of piling chips up to 7 m high is very common in the Nordic countries but it causes mass and energy losses between 8 and 12% per half year (Lehtikangas 1999).

A 10% loss in energy during storage could amount to the loss of 100,000 EUR (based on the price 15 $EUR \cdot t^{-1}$ or 29 $EUR \cdot MWh^{-1}$) for a bigger heating district central with a consumption of 0.25×10^6 t dry matter. Modern combustion plants, especially those with a fluidised bed, demand a certain fuel moisture content for good combustion and a significant part of the heat from the vapour is recycled in a condenser.

Unfortunately there are very few published works dealing with how to reduce storage losses, and with the risk of self-ignition in comminuted fuel wood chips (Armstrong 1973). Formerly, charcoal was compacted with a tracked machine to avoid self-ignition (Dungan 1981). At Domsjö Fiber AB, Örnsköldsvik, Sweden, this technique was used on an old store of comminuted mixed softwood chips and it was even possible to extinguish a fire. The same material was stored for another year and no fire occurred during that period. New methods are coming up. Afzal et al. (2010) tested a new type of ventilating fibre cloth which would be much easier to apply on a pile of chips instead of a roof mentioned earlier. This type of fibre cloth could stop rain water from entering into the pile but still allowed the ventilation of humid air from the pile.

The aim of this work was to evaluate in a large-scale experiment: (*i*) the influence of pile compaction on energy loss during chip storage, (*ii*) the effect of a ventilation tarp covering on chip pile drying, (*iii*) the effect of compaction and ventilation tarp on changes in energy content in a chip pile after 5.5 months of outdoor storage.

MATERIAL AND METHODS

The material used in this study originated from Latvia. The composition was of mixed small stem and logging residues mainly from coniferous trees (mostly spruce) with bark and some needles. The particle size distribution is shown in Table 1. Information about the material is scarce. It was most likely sent to Sweden within 6 months after felling. It was transported by boat from Riga, Latvia, to the harbour Örnsköldsvik, Sweden, at the end of May 2010. The loading and unloading processes meant

Table 1. Particle size distribution in the Riga mix according to SS 18 71 74:2 (n = 3)

Particle size (mm)	> 45	15–45	5–14	3–5	< 3
% of dry matter	2.6	32.2	33.9	10.4	20.6

that the material was mixed at least twice. The material used was generously supplied by Domsjö Fiber, Örnsköldsvik, Sweden.

The material was transported by chip lorries from the harbour to an asphalted area about 25 km south of Örnsköldsvik. The lorries first passed a measurement station (certified weighbridge by the national measurement society, 100 kg accuracy) with a lorry scale and at the same time samples for moisture determination were taken according to methods used at Domsjö Fiber (Swedish Wood Measuring Association 1998). Each pile demanded 6–7 lorry loads of about 40 t per each and the material was tipped at separate places.

Each pile contained 240 t wet weight of wood chips. The control consisted of normally stacked (stack) material and the tested compacted pile, here called cake, was the second pile. Additionally, a ventilating tarp – TopTex (TenCate Geosynthetics Austria GMBH, Austria) was used to test the effect of a covering material. Formed as a single Latin square, the design was as shown in Table 2. In total the investigation consisted of almost 1,000 t of wood chips (dry weight).

The cakes were formed on June 7–8 with a tracked, 14 t machine (Case 1150E). It had a ground pressure of about 55 kPa with track length of 2.45 m and width of 0.51 m. The operator first pushed the fuel material together into a pile with the blade, then made a ditch for the temperature gauges and net bags. Then the cake was formed and compacted to a uniform round shape. The cakes were 19 and 19.5 m in diameter, with a slope of 24° and a height of about 3.4 m. Tested with a cone penetrometer (Deepak Kumar 2011), 30° angle and base 21 mm, penetration rate 3 cm·s^{-1}, the resistance was about 950 kPa (n = 10). The June 9 stacks were made with a Volvo L60E loader with a snow bucket and a rake on a pole. Also, a ditch was made in the middle of the pile for the temperature sensors and net bags. Then all chips were shovelled up.

These stacks were 22–27 m long, 9–12 m wide and 4.1–4.2 m high. The slope was about 40° and the cone resistance at the bottom was 480 kPa and at the top 140 kPa (n = 10 and 6).

24 marked nylon net bags with 1 mm mesh size were filled with 4–5 kg wet weight of the same chip material as in the piles (Bergman, Nilsson 1967). Also, eight small buckets with a lid were filled and three of them were used to test the heating value and for sieving analyses. The rest were stored in a cool place for later analyses.

Table 2. Design of the storage experiment

Shape			
Stack		cake	
Uncovered (control)	covered (TopTex)	uncovered	covered (TopTex)

Moisture content (MC) determination is a very crucial component for the determination of energy content in biofuels. Hägg (2008) studied the variation in moisture content of chipped material coming to the Umeå Energy district heating plant producing almost 1 TWh·yr^{-1} and concluded that in some cases 7 samples per 40 t load would even be too few to meet the 95% confidence interval (Swedish Wood Measuring Association 1998).

The temperature sensors were K-type (NiCr-Ni) thermo elements, all were checked before use. The end of the element wires was protected with shrink tubing to avoid metal contact with the woody material. The wires were taped up along a 4 m wooden stick with one sensor at 1 m and one sensor at 4 m, so the position of the sensors would be known. The first wooden stick was placed level, 0.5 m above ground, the second at 1 m, the third at 1.5 m height, and the fourth one along the slope of the pile about 0.1–0.2 m below the surface. The sensors were connected to a 4-channel logger with registration of temperature every 30 min. In each pile net bags with chips were placed next to the temperature sensors for the three lowest levels. Two weather-reading stations were placed close to the piles to record the general weather conditions during the test period.

On June 15, the TopTex fibre tarp was rolled out on the piles to be covered. The cloth was anchored to wooden sticks with screws to prevent blowing away. Three rolls, 6 × 50 m each, were used for two covered piles. TopTex is a ventilating tarp made of geosynthetics (polyethylene) which can ventilate gases and at slopes of more than 20° rain will run off the tarp. The material has a unit weight of 200 g·m^{-2} and is produced by TenCate Industrial Fabrics.

One week later a laser triangulation measurement was done to determine the volume of each pile (Fig. 1). The piles were quite similar in size although the cakes were compacted but the stacks were not, which is also indicated by the calculated densities at the start of the piles (Table 3).

The trial was stopped at the end of October and the beginning of November 2010. Before stopping it, a further laser triangulation of the piles was done to check the pile shrinkage. After that, the piles were pulled down and the material was transported by lorries back to Domsjö Fiber and scaled.

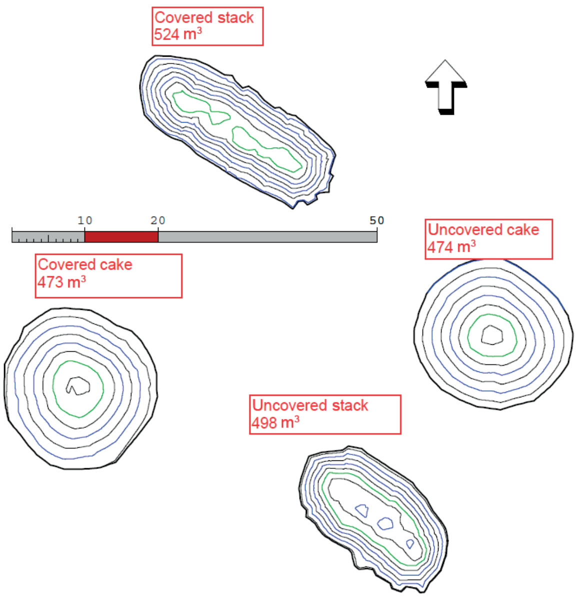

Fig. 1. Volume determination of the piles on 21 June, accuracy about ± 1%, 0.5 m between equidistant

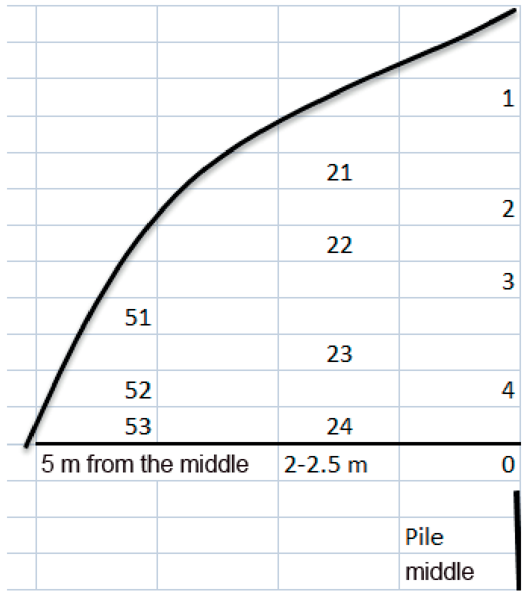

Fig. 2. Schematic drawing of the sampling points for moisture determination in the cross section of the piles

At the same time samples for moisture determination were taken. When tearing down the piles and reaching the middle of the pile a cross section was cut clean. The pile was photographed and samples for moisture content determination were taken. The net bags containing chips and the temperature sensors were also removed. An infrared camera was used to localize heat zones in the pile.

The moisture samples were taken in a grid system as shown in Fig. 2. The same material was also used for determination of calorimetric heat values. Closed buckets taken at the start were used for determination of ash content. The net bag green weight was measured on the spot. The moisture content was determined at 105°C according to SS 18 71 70 (nowadays EN-). The net bags were dried unbroken to avoid the loss of material. All data from the temperature loggers and weather stations were downloaded to a notebook.

Heat (SS-EN 194918) value and ash content were determined in the fuel lab, Umeå, Sweden (SS 18 71 70).

RESULTS

Shrinkage

Temperature and precipitation in 2010 were quite normal for a Swedish summer (Fig. 3) with occasional heavy rain showers at the beginning of August. Frost occurred at the end of October.

The laser triangulation showed that the volume of the piles shrunk only between 3 and 6%, (Tables 1 and 3). The uncovered cake showed shrinkage of almost 6%. The basic density in the cakes as compared to that of the stacks was, at the end of the trials, only slightly influenced by the compaction from the crawler tractor, indicating that it is difficult to compact wood chip piles at 50 to 60 kPa pressures. Nevertheless, it was considerably more difficult to dig out the net bags from the cakes compared to the stacks. The low shrinkage in the piles after 5.5 months of storage indicated that material losses in the experiment would be quite small.

Table 3. Size of piles, densities and shrinkage in volume before the start of experiment and 5.5 months later

Pile		Before storage			After storage			
		volume (m^3)	density ($t \cdot m^{-3}$) green	density ($t \cdot m^{-3}$) basic	volume (m^3)	density ($t \cdot m^{-3}$) green	density ($t \cdot m^{-3}$) basic	shrinkage (%)
Stack	uncovered	498	0.48	0.24	481	0.48	0.22	3.4
	covered	524	0.46	0.22	505	0.40	0.20	3.6
Cake	uncovered	472	0.52	0.26	444	0.57	0.22	5.9
	covered	473	0.50	0.24	458	0.50	0.23	3.2

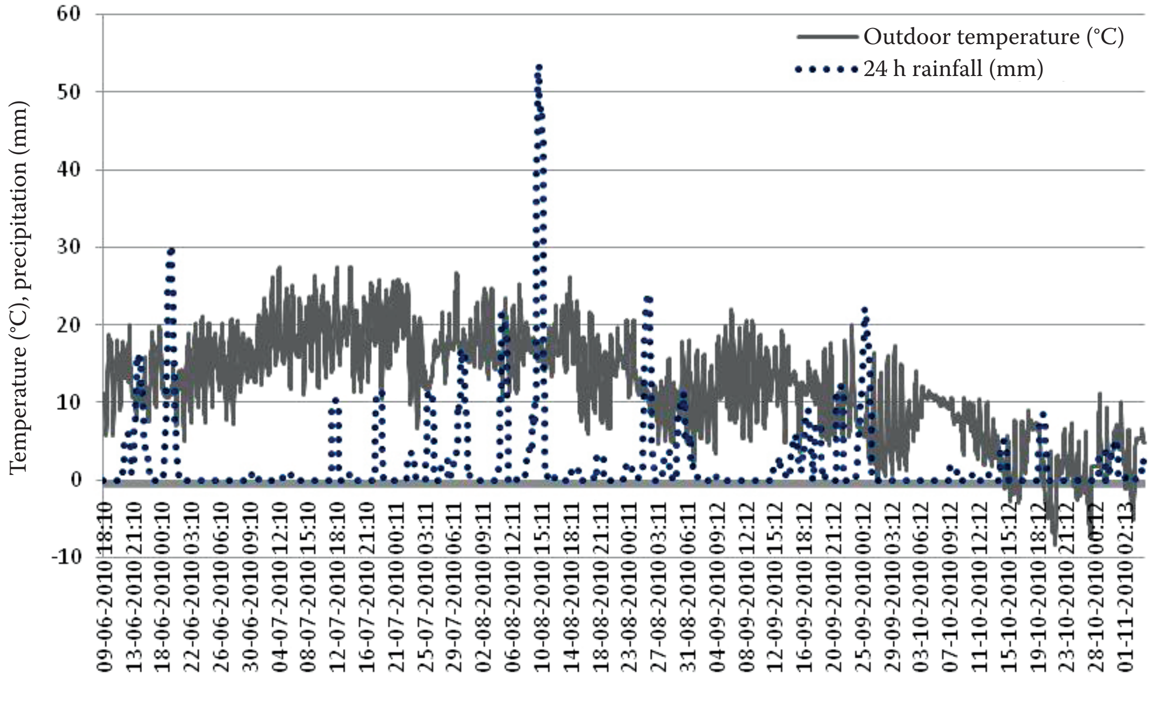

Fig. 3. Temperature and rainfall from the weather station during the storage experiment

Temperatures

The temperature development in all piles followed a quite similar pattern (Fig. 4). Within a week the sensors reached the maximum temperature of 65–70°C. Both types of piles reached about the same maximum temperature but at different positions, top for the stacks and innermost for the cakes. After about two months the temperature at most positions was below 60°C except for the innermost sensors in the cakes. The TopTex cover on the piles had only a minor effect on the temperature development. However, the uncovered cake showed a much more fluctuating temperature on the top than the uncovered stack. At the end of September most zones in the pile still had a temperature of about 50°C except for the outer parts of the stacks where the temperature was lower.

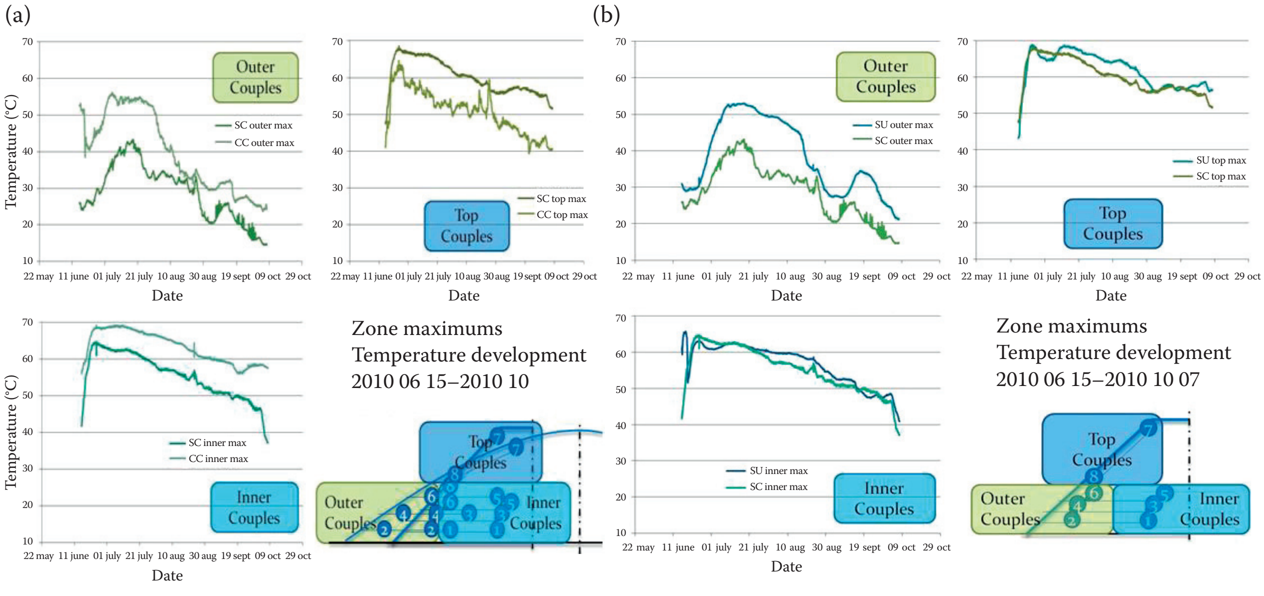

Fig. 4. Temperature development (maximum values per day) in the wood chip piles in the top, outer and inner section, the numbers denote temperature sensors: covered cakes and stacks (a), uncovered and covered stacks (b)

SC – covered stack, CC – covered cake, SU – uncovered stack

Table 4. Dry matter – DM (%, t) and standard deviation (SD) according to the local timber measurement society at the start and end of experiments

Pile		Out from Domsjö			Back to Domsjö, end of storage		
		DM		SD	DM		SD
		(%)	(t)		(%)	(t)	
Stack	uncovered	49.89	118.70	8.74	45.52	104.32	8.38
	covered	48.94	117.86	1.3	48.98	98.61	6.88
Cake	uncovered	49.38	112.00	0.86	39.19	99.27	5.07
	covered	48.93	115.84	1.29	45.74	104.25	8.87
Sum			474.4			406.5	
Average		49.3			44.9		

Moisture content

The energy content of a pile of wood chips usually depends on four different parameters: weight of the material, moisture content, heat value of the material and the ash content (formulas later on). Modern lorry scales are quite precise if regularly calibrated and the lorry passes both loaded and unloaded with the difference being caused by the load. More critical is how to determine the moisture content. The accepted Swedish method (Swedish Wood Measuring Association 1998), SS 18 71 70, is usually based on one sample taken from the top of the load, often on the trailer. This sample was then dried in an oven at 105°C for 24 h (Swedish Wood Measuring Association 1998). The dry matter (DM) content is then multiplied by the load (Eq. 1):

$$\left(\mathrm{DM}/100\right)\times \text{wet weight} \quad (1)$$

In our case, the material was relocated at least three times and it was accepted as the starting value of DM content. However, after checking the standard deviation, it was clear that at least some lorry loads had rather varying DM content (Table 4).

According to these measurements the moisture content in the piles had decreased somewhat and lost about 70 t DM (Tables 3 and 4). This was somewhat strange since the piles had lost only about 3–6% in volume (Eq. 2):

$$0.04\times 1{,}969\left(\text{green weight}\right)\times 0.22 = 17.3 \text{ t DM} \quad (2)$$

The standard deviation in DM determination indicated that there was quite a lot of variation between lorry loads going back to Domsjö (which will be further discussed later on).

However, precautions were already taken at the end of the storage experiment and moisture samples were taken according to the pattern as shown in Fig. 2.

Net bags

The net bags were dug out at the end of the experiment, but two bags in the compacted piles were very difficult to get out and they broke. The broken bags were wet weighed directly after finishing (Table 5) in a separate laboratory. The field scale had a precision of only ± 50 g, which could cause a deviation of about ± 2.5% of the determined moisture content but the external laboratory had a higher precision.

According to the average values (Fig. 5, Table 5) from the net bags only minor losses occurred in the piles although there were high standard deviations in some of the piles. Looking at the places where the net bags were placed, the lowest loss (highest DM)

Table 5. Dry matter (DM) content in net bags before and after storage (n = 5–6 per pile)

Pile		Net bags					
		before storage		after storage			
		dry weight (kg)	DM (%)	dry weight (kg)	DM (%)	SD	diff. DM (%)
Stack	uncovered	2.51	52.0	2.33	35	2.02	–7.15
	covered	2.35	49.9	2.21	65.6	2.98	–5.80
Cake	uncovered	2.50	52.9	2.57	52.9	14.23	2.94
	covered	2.35	52.0	2.37	47.9	13.63	2.94
Average		2.43		2.37			

SD – standard deviation

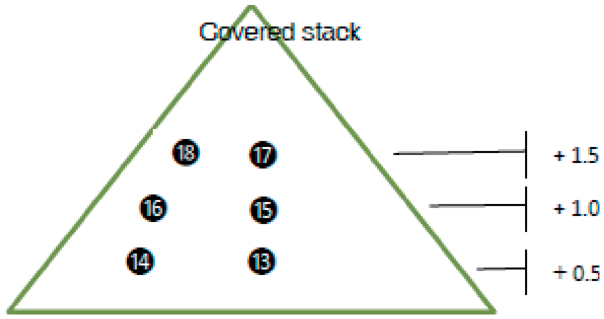

Fig. 5. Positions of the net bags as an example from the covered stack as a model for all stacks and where the net bags were positioned and the height above ground

Table 6. Dry matter content in different piles calculated after ArcGis (Version 9, 2009) modelling of area weighted (cross section) or volume weighted and the average dry matter content according to cross samples (n = total 43)

Pile		Dry matter (%)	
		area based	volume based
Stack	uncovered	48.7	49.5
	covered	61.4	61.4
Cake	uncovered	54.5	53.6
	covered	43.7	43.2
Average		52.1	51.9

occurred mainly in the covered stack and in the middle (place 17 and 15) which was also the dry parts (Fig. 6b).

Sampling for MC was done according to the schedule in Fig 2. Determination of moisture content was followed by determination of energy content. The sampling was used together with infrared pictures (Fig. 6c) and ordinary photos of the cross section (Figs 6a, b) to model based on area and volume with the help of ArcGis (Version 9, 2009). The volume was calculated as columns through the whole pile at that level. As seen in Table 6, the difference between area and volume weighted DM was not very large but resulted in a much drier pile than recorded by the measurement society at Domsjö.

(a)

(b)

(c)

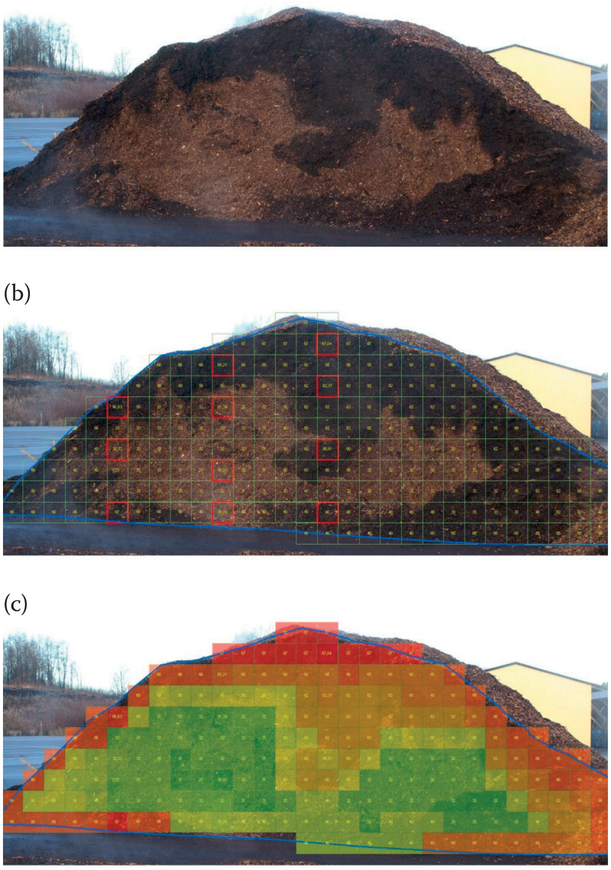

Fig. 6. Uncovered stack in a cross-section at the end of the experiment: cross section at the end (a), squared net with values of moisture content for locations where it was measured (b), coloured moisture zones with ArcGIS (Version 9, 2009) based on (a) and (b) as basis for determination for calculation of volume weighting of moisture content in the pile – in red (c)

Energy

Did perhaps the energy content differ between the piles? The first step was to analyse how the energy is calculated. The value is the inherent energy and what is usually determined in laboratories. Then adjustments are made for H in the water produced during combustion, roughly 6% (Andersson, Burvall 1986). Three samples gave the heat value called the effective heat value (Eq. 3):

$$19.91\ \text{MJ·kg}^{-1}\ \text{DM} \times 0.94 = 18.7\ \text{MJ·kg}^{-1}\ \text{DM}\left(= W_{\text{eff}}\right) \quad (3)$$

where:

W_{eff} – effective energy content (MJ·kg^{-1} DM).

At delivery the lorry was weighed as mentioned above and as adjustment for possible moisture in the fuel was done according to Eq. 4:

$$W_{\text{eff}}\ \text{delivered} = \left(\frac{\left(W_{\text{eff}} - 2.45\right)\times\left(100 - \text{DM}\right)}{\text{DM}} \times \frac{1}{3.6}\right) \times$$
$$\times\, \text{dry material in tonne} \quad (4)$$

where:

W_{eff} delivered – energy content at delivery adjusted for moisture content (MWh),

3.6 – conversion factor from MJ to Wh,

2.45 – water vaporization (MJ·kg^{-1}).

It was assumed that wet chips would have lower energy content but the analyses showed no dif-

Table 7. Heat values of the chips from different piles (heat value) and the effective energy content – W_{eff} (n_{total} = 12)

Pile		Heat value (MJ·kg^{-1} DM)		W_{eff} (MJ·kg^{-1} DM)
		dry part	wet part	
Stack	uncovered	19.86	19.60	18.55
	covered	19.89	20.01	18.73
Cake	uncovered	20.20	20.13	18.96
	covered	19.73	19.87	18.61
Average (SD)		19.92 (0.228)	19.90 (0.199)	18.72

SD – standard deviation

ference between dry and wet parts in the pile (Table 7). Thus the whole pile had about the same energy content, and there was no need for any adjustment due to MC.

Something was wrong with the local timber measurement society's measurement because 69 t of material (DM) and 381 MWh were lost during the experiment and it did not fit with our measurements. A check revealed that they used another adjustment factor in the computer (17.7 instead of the real value 18.7 MJ·kg^{-1} DM at DM 65%, r^2 = 0.9993) adjusting after adjustment for moisture, thus correcting twice for moisture. Thus, they had two things that were wrong: the one was bad sampling, and the other their computer had wrong parameters for the calculations of energy content although they should be the official national measurement organisation.

For the sale of biofuels an adjustment is done for ash content: W_{eff} (1 – ash), thus 18.7 × (1 – 0.06) = 18.7 × 0.94 = 17.6, which in our case had some but minor influence on a difference (Table 8) between the piles (Swedish Wood Measuring Association 1998). Ash is given in percent of DM (e.g. 0.042).

The ash values were very high for this kind of material indicating that the sand had contaminated delivered material. The ash content in all piles was highest on the outer edges and had actually decreased in the centre.

Some of the buckets saved at the start were checked for moisture content. They appeared to be wetter (DM = 47.8 wt%) than the local timber measurement society's measurement at the start (DM = 49.4 wt%) but were now taken as a starting value (Table 9). After that, the values looked reasonable and all cakes lost some substance and all piles covered with TopTex lost very little and even gained some energy due to the drying out of the piles. Thus, the compaction of stored chips prevents fire but does not prevent the loss of energy.

Summing up, the measuring principles used by the local timber measurement society do not work if precision is required. One sample from the top of a trailer did not meet their own standard indicating that more samples must be taken to be within a 95% confidence interval ± 2% (Swedish Wood Measuring Association 1998). Cakes lost material as well as the uncovered stack. The covered stack even increased the energy content although it lost some substance (Table 9).

If decomposition occurs, mainly holocellulose would disappear leaving a higher content of lignin, which could explain the increased energy content (Richardson et al. 2002; Afzal et al. 2010). 144 MWh and 34 t were lost, which means that only 1.1% of the energy per month disappeared thanks to the TopTex cover.

DISCUSSION

Few published papers have determined total mass and energy from before and after an investigation. In most cases these parameters were determined with help of net bags, which is questionable according to the present study.

Nurmi (1999) did a similar study to the present one with chipped logging residues mainly from

Table 8. Ash content in the piles separated per pile and location in the pile (n_{total} = 14)

Location	Ash content after 5.5 months storage (%)				At start
	stack		cake		
	uncovered	covered	uncovered	covered	
Top	3.2	6.5	4.3	5.6	
Centre	5.1	3.5	3.1	5.8	5.5
Outer	4.3	9.5	6.4	6.1	
Average	4.2	6.5	4.6	5.8	

Table 9. Summary of the experiment with adjusted values for dry matter (DM) including calculated energy content before and after 5.5 months storage

Pile		Out from Domsjö				Back to Domsjö					
		wet (t)	adjusted DM (%)	DM (t)	W_{eff} lev (MWh)	wet (t)	DM (%)	DM (t)	W_{eff} (MJ·kg^{-1} DM)	W_{eff} lev (MWh)	difference from the start
Stack	uncovered	241	52.2	126	575	229	49.4	113	18.55	534	–41
	covered	238	52.2	124	568	201	61.4	123	18.75	588	20
Cake	uncovered	247	52.2	129	590	253	43.2	110	18.61	470	–120
	covered	237	52.2	124	566	228	53.6	122	18.96	563	–3
Sum		939		502	2,298	912		468	18.72	2,155	–144

lev – at delivery

spruce. The interesting result from that study was that carbon content increased after 5 months storage from 50 to 51.3% and H decreased from 6.6 to 5.7%. Thus, the above assumed value of 6% for H could be close to the real content although it was not measured here.

The heated air in the pile moves upwards to the cooler surface areas and simultaneously transports moisture to the surface and thus the inner parts dry out. To dry out a pile the ventilation must be good and this can be accomplished with a cone-shaped pile. However, the pile should not be higher than 7 m because of heat development inside the pile (Lehtikangas 1999).

The presented large-scale experiment revealed that:

(*i*) Pile compaction resulted in a higher energy loss during chip storage than just being stacked. The compacted pile had too little ventilation to dry out (Table 9) but compaction also prevents a fire to start;

(*ii*) The effect of a ventilation tarp cover on the chip pile caused an astonishingly effective drying out, which could result in an increase of energy in the pile; the tarp + labour to cover the whole pile was almost paid by the energy increase and the tarp could likely be reused over three years;

(*iii*) The 5.5 months outdoor storage caused on average about a 1% loss of energy per month but in the worst case a loss of more than 14% occurred (the cake uncovered).

Since MC is such an important factor for energy determination, it must be determined with better precision than practiced today. A seller of biofuels could lose 2.2 MWh × 29 = 64 EUR per lorry load if MC is wrongly determined by 15%, which occurred here (16%).

Sweden adopted a new wood measurement law in 2015 and according to our findings it seems to be necessary. In the present case they lost about 2% on average at the lorry measurement of MC and apparently also the control for confidence interval, but also they had wrong parameters in the computer further 1% of the heat value. However, in this case it had a minor influence since the bioenergy belonged to the same company for the whole time from start.

CONCLUSIONS

Detailed and precise information about moisture content is needed, since it is an important factor for the determination of energy content. But future storage studies should be based on energy content before and after storage to reveal the whole effect of storage to avoid the miscalculation of energy content.

Net bags cannot be trusted for determination of average moisture content in piles unless their MC can be referred to a specific volume in the pile and their location being exactly known.

Compaction of piles did not work for the preservation of woody material but may prevent the occurrence of fires.

Ventilating tarps such as TopTex worked very well for the storage of woody chips and further studies will be done to learn the mechanical and chemical effects of the tarp.

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References

Afzal M.T., Bedane A.H., Sokhansanj S., Mahmood W. (2010): Storage of comminuted and uncomminuted forest biomass and its effect on fuel quality. BioResources, 5: 55–69.

Andersson E., Burvall J. (1986): Heat values and factors influencing the heat value. Bioenergi No. 4. (in Swedish)

Armstrong J. (1973): Spontaneus Combustion of Forest Fuels: A Review. Information Report FF-X-42. Ottawa, Forest Fire Research Institute: 14.

Back E.L., Allen L.H. (eds) (2000): Pitch Control, Wood Resin and Deresination. Atlanta, TAPPI Press: 340.

Barontini M., Scarfone A., Spinelli R., Gallucci F., Santangelo E., Acampora A., Jirjis R., Civitarese V., Pari L. (2014): Storage dynamics and fuel quality of poplar chips. Biomass and Bioenergy, 62: 17–25.

Bergman Ö., Nilsson T. (1967): On Outside Storage of Aspen Chips at Hörnefors' Sulphite Mill. Research Notes No. 55. Stockholm, Royal College of Forestry: 60. (in Swedish with English summary)

Deepak Kumar S. (2011): Prevention and control module for spontaneous combustion of coal at coal yards. Available at http://www.energycentral.com/c/gn/prevention-and-control-module-spontaneous-combustion-coal-coal-yards

Dungan K.W. (1981): Fire Protection in Coal Handling Facilities: New and Retrofit. Technology Report 81-10. Oak Ridge, Society of Fire Protection Engineers: 8.

Fuller W.S. (1985): Chip pile storage – a review of practices to avoid deterioration and economic losses. TAPPI Journal, 88: 48–52.

Greaves H. (1975): Microbial aspects of wood chip storage in tropical environments. Australian Journal of Biological Science, 28: 315–322.

Hägg K. (2008): Measurement of Tree Parts and Forest Wood Chips at Dåvamyran, Umeå Energy. Report No. 223-2008. Umeå, Swedish University of Agricultural Sciences: 57. (in Swedish with English summary)

Jirjis R., Pari L., Sissot F. (2008): Storage of poplar wood chips in northern Italy. In: Proceedings of the World Bioenergy Conference and Exhibition on Biomass for Energy, Jönköping, May 27–29, 2008: 107–111.

Kossuth S.V., Roberts D.R., Huffman J.B., Wang S.C. (1982): Resin acid, turpentine, and caloric content of paraquat-treated slash pine. Canadian Journal of Forest Research, 12: 489–492.

Kossuth S.V., Roberts D.R., Huffman J.B., Wang S.C. (1984): Energy value of paraquat-treated and resin-soaked loblolly pine. Wood and Fibre Science, 16: 398–402.

Lehtikangas P. (1999): Handbook for Storage of Bio Fuels. Uppsala, Swedish University of Agricultural Sciences: 116. (in Swedish)

Mohan D., Pittman C.U., Steele P.H. (2006): Pyrolysis of wood/biomass for bio-oil: A critical review. Energy & Fuels, 20: 848–889.

Nurmi J. (1999): The storage of logging residue for fuel. Biomass & Bioenergy, 17: 41–47.

Nylinder M., Thörnqvist T. (1980): Storage of Stump Wood in a Simulated Environment. Report No 113. Uppsala, Swedish University of Agricultural Sciences: 45. (in Swedish with English summary)

Richardson J., Björheden R., Hakkila P., Lowe A.T., Smith C.T. (eds) (2002): Bioenergy from Sustainable Forestry: Guiding Principles and Practise. Dordrecht, Kluwer Academic Publishers: 344.

Swedish Wood Measuring Association (1998): Common and special directions for measurements of bio fuels. Available at http://ny.sdc.se/admin/PDF/pdffiler_VMUVMK/M%C3%A4tningsinstruktioner/M%C3%A4tningsinstruktion%20f%C3%B6r%20biobr%C3%A4nsle%2C%20VMR%201999.pdf (in Swedish)

Thörnqvist T. (1982): The Importance of Cover and Air Under-base with Storage of Fuel Chips. Report No. 127. Uppsala, Swedish University of Agricultural Sciences: 82. (in Swedish with English summary)

Thörnqvist T. (1985): Drying and storage of forest residues for energy production. Biomass & Bioenergy, 7: 125–134.

Zabel R.A., Morrell J.J. (eds) (1992): Wood Microbiology: Decay and its Preservation. San Diego, Academic Press, Inc.: 476.

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