

Aus dem Institut für landwirtschaftliche Verfahrenstechnik
der Agrar- und Ernährungswissenschaftlichen Fakultät
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**Dry matter losses
during storage of wood chips from
short rotation coppice**

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Abbreviations

ash	ash content on dry basis
ash _{bark}	ash content of bark on dry basis
ash _{chip}	ash content of the chips on dry basis
ash _{wood}	ash content of wood without bark on dry basis
ash _c	calculated ash content based on bark content on dry basis
bc _(branch)	bark content of branches on dry basis
bc _{tree}	bark content of whole tree on dry basis
bc _{tree}	bark content of whole tree on dry basis
C	carbon content of the fuel on water-free reference basis
C1 – C4	cross-sections 1 – 4
CFU	colonisation by thermophilic mould fungi
D1	first sampling date
D2	second sampling date
day _i	storage day at time i
db	dry basis
H	hydrogen content of the fuel on water-free reference basis
HHV	higher heating value at constant pressure on water-free reference basis
i	time
k	evaporation heat including the volume work of the water formed from the hydrogen during combustion at 25°C (0.2122)
L	dry matter loss
L _(ash)	dry matter loss via ash content
L _(ash c)	dry matter loss via calculated ash content based on wood-bark-ratio
L _(sb)	dry matter loss via sample bags
LHV	lower heating value on wet basis
LHV _{out}	lower heating value of mass on wet basis retrieved from storage
M1	method 1: determining mass changes and moisture content of samples from balance bags, distributed across a section of the storage pile (reference method)
M2	method 2: determining mass changes and moisture content of samples from balance bags arranged in measuring columns in the pile core
M3	method 3: determining mass changes through periodic weighing of the entire pile and moisture content of samples from pile cross sections
M4	method 4: determining ash contents from samples in balance bags, arranged in measuring columns in the pile core

$m_{b \text{ (branch)}}$	bark mass of branches on dry basis
$m_{b \text{ (stem)}}$	bark mass of stem on dry basis
m_{in}	mass of material taken into storage
m_{out}	mass of material retrieved from storage
$m_{w \text{ (branch)}}$	wood mass of branches on dry basis
$m_{w \text{ (stem)}}$	wood mass of stem on dry basis
P1	platform 1
P2	platform 2
$q_{v,gr,d}$	calorific value at constant volume on water-free reference basis
S	sulphur content of the fuel on water-free reference basis
SDCH	stem diameter at cutting height (10 cm)
SHV	specific heating value, defined in mega joule per kilogram input material
w	moisture of the fuel in analysis on water-free reference basis
wb	wet basis
x	moisture content, defined as the proportion of mass of water in the wet material (on wet basis)
x_{branch}	branch proportion on dry basis
x_{in}	moisture content of the material taken into storage
x_{out}	moisture content of the material retrieved from storage
ΔQ_v	evaporation enthalpy of the water (2.441)

General introduction

Conventional agriculture is characterised by intensive cultivation of a few, mainly annual crops that are constantly repeated in crop rotation [STATISTISCHES BUNDESAMT, 2016]. The introduction of the German Renewable Energy Act (EEG) in 2000 and particularly its amendments in 2004 and 2009 formed a suitable basis for producers to extend their conventional production of foodstuffs and feedstuffs to include the provision of electricity and heat [EEG, 2000; EEG, 2004; EEG, 2009]. In this way the share of renewable energy sources in satisfying Germany's primary energy demand was increased over the last 15 years from 1.3% to 12.6% [AGEB, 2016]. The use of biomass in over 600 biomass power and heating plants accounts for the largest share (7.1%). The number of biogas plants in Germany doubled during the last 10 years, and with it the area under maize cultivation to 2.6 million ha [FNR, 2016]. Together with the acreage for wheat, barley and canola, more than 50% of the agriculturally used farmland in Germany is now cultivated with just four crop species [STATISTISCHES BUNDESAMT, 2016]. The accompanying spread of pests and diseases is being countered with rising use of pesticides in order to secure the yields in the long term [MÖCKEL ET AL., 2015].

Moreover, by now alternative methods are established which enable the supply of resource efficient, sustainable and economically viable energy sources. In short-rotation coppices fast growing trees with shoot-forming capacity, such as for example poplar, willow and robin, are being established on a decentralised basis. As permanent crops they are harvested chiefly on a short-rotation basis every two to five years using a wide variety of machinery and equipment [MURACH ET AL., 2008; SANTANGELO ET AL., 2015]. The production is oriented to quality parameters specified by the customers. The wood chip quality is determined by the desired chip format without contaminants and impurities, low fine and oversize shares, low ash contents, high calorific values, and in particular by low moisture contents [EASSON ET AL., 2011; BARTSCH ET AL., 2015].

Agricultural wood cultivation offers above all ecological benefits alongside with commercial benefits, such as a stable high yield of approx. $10 \text{ t}_{\text{db}} \text{ ha}^{-1} \text{ a}^{-1}$ (poplar) and just one planting and regular harvesting at a time which is convenient for labour management, [BEMMANN & KNUST, 2010].

On the one hand minimal use of fertilisers and pesticides reduces the N_2O emissions by more than 50% by comparison to rye cropping. On the other hand, the perennial trees enrich the carbon bound in the soil by up to $1600 \text{ kg ha}^{-1} \text{ a}^{-1}$ with corresponding humus formation and promotion of additional biodiversity [BIELEFELDT ET AL., 2008; SCHOLZ ET AL., 2011; BALASUS ET AL., 2012]. Despite this, political and other barriers as well as process-specific uncertainties are inhibiting the spread of these crops [EUROPEAN UNION, 2014; BOLL ET AL.,

2015]. For this reason the area under cultivation in Germany is currently only approx. 7000 ha [PECENKA ET AL., 2014; FNR, 2016].

Agricultural timber is harvested in leafless condition with moisture contents between 50 and 60%, generally in winter (January - March) [REEG ET AL., 2009]. However, usually only wood chips with moisture contents of around 30% are demanded from customers. By natural drying of the wood chips, a six-month storage period is required to achieve this level [SCHOLZ ET AL., 2011]. The most cost-efficient storage method is to heap wood chips in large piles out in the open, which have to be covered with appropriate non-woven or fabric cover, in order to use the naturally occurring drying process. The temperature inside the pile can rise at times to over 60°C [FERRERO ET AL., 2011; LIN & PAN, 2014; PECENKA ET AL., 2014, PARI ET AL., 2015]. Reasons for this are suspected to lie in the residual respiration of wood cells and in microbiological and thermochemical processes that can cause up to 30% dry matter losses, which in turn has a negative effect on the profitability of the overall process. In preceding studies, it was shown on a technical scale (10 m³) that dry matter losses can be reduced and at the same time drying can be accelerated with increasing chip format [SCHOLZ & IDLER, 2005; KRISTIN & WETZEL, 2016].

Up to now, dry matter losses are measured and assessed almost exclusively at the end of the storage period [HEINEK ET AL., 2013; MANZONE ET AL., 2013; LIN & PAN, 2014; BARONTINI ET AL., 2014; WHITTAKER ET AL., 2016]. Accordingly the loss curve over the storage period is not analysed. On the one hand this makes it impossible to determine a favourable time for removal from storage. On the other hand, it is not possible to identify the connections between pile temperature, gas concentration, calorific values, ash content, moisture content and dry matter losses in order to draw conclusions about possible causes of dry matter losses.

Furthermore, the data on dry matter losses vary depending on the different methods of determination. Additional dependence are resulting from the type of wood as well the region of growing and storage, pile dimensioning, chip format as well as type and number of sampling points [SCHOLZ & IDLER, 2005; HORVATH ET AL., 2012; MANZONE ET AL., 2013; BARONTINI ET AL., 2014, GEJDOS ET AL., 2015; ROUTA ET AL., 2015]. While SCHOLZ & IDLER (2005) investigated dry matter losses on removal from storage of different poplar wood chip formats in 10 m³ piles in North-East Germany with the aid of balance bags, WHITTAKER ET AL. 2016 calculated dry matter losses in England partly by weighing fine chips from willow on storage intake and removal from storage, taking a 320 m³ pile as an example. HEINEK ET AL. 2013 determined dry matter losses of fine chips from spruce in Italy using balance bags in a 960 m³ pile. Not only regular data throughout the storage of piles on a practice scale, but

also clear design specifications for the experiment as well as for representative sampling and reliable methods of determining the dry matter losses of different chip formats are lacking here.

The overall aim of this study was to quantify dry matter losses during storage of wood chips in practice-scale piles. Reliable and convenient methods were developed and applied for the first time regularly during the storage period of six months. Conclusions regarding microbiological and chemical degradation processes were to be drawn by determining storage parameters such as pile temperature, gas concentrations, calorific values, ash content, moisture content and dry matter losses. Thus, fundamentals are available to enable detailed research on the causes of dry matter losses in the future. For this it was necessary to develop a novel sampling system with which storage parameters such as pile temperatures, O₂ and CO₂ concentrations, calorific values, ash contents, moisture contents, and in particular dry matter losses could be determined regularly during the whole storage period without disturbing the pile behaviour. Using two piles with different chip formats, the suspected advantage of coarse chips – that they dry more quickly than fine chips with lower dry matter losses – was to be verified on a practice scale during storage (**Chapter one**).

Alongside the balance bag method, alternative methods for simple and representative determination of dry matter losses were developed. On the basis of ash contents, it was examined whether dry matter losses can be determined at any time without first installing sample bags in the pile (**Chapter two**).

In a further approach, dry matter losses during storage of wood chips were determined by a platform with continuous weighing function of the pile. The results were compared with those of the alternative methods and set against the balance bag method as reference (**Chapter three**).

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Chapter one

Open-air storage of fine and coarse wood chips of poplar from short rotation coppice in covered piles

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Abstract

The cultivation of short rotation coppices (SRC) on agricultural land represents an economically and environmentally promising option for sustainable provision of bioenergy. Not only the further development of efficient harvesting machinery, but also the development of efficient harvest-optimized storage systems are necessary to implement cost-efficient cultivation and use strategies for SRC in practice. The storage of fine wood chips from poplar harvest with a forage harvester results in high dry matter losses of up to 25%. Tractor-mounted mower-chippers can harvest coarse wood chips that might possess more favourable storage and drying properties. The main objective of the current research project was to develop and perform a storage experiment in which the storage behavior of fine and coarse wood chips could be examined and compared in detail over a period of nine months. In this experiment two covered storage piles (height 3.5 m), with over 500 m³ fine and coarse wood chips respectively, were examined under practice scale conditions in Germany. After nine months of storage the fine chips in the core of the storage pile had dried to a moisture content of 34% with dry matter losses of 22%. Coarse chips, on the other hand, achieved a moisture content of 29% and dry matter losses of 21% in the same period. The maximum moisture content of 40% required by heating plants in practice is achieved by fine chips after 6.5 months and by the coarse chips already after 3.5 months.

Keywords

Short rotation coppice, poplar, wood chip, storage, drying, dry matter loss

Highlights

1. The influence of chip size on storage of poplar wood was examined in detail.
2. The time profile of temperature, loss, moisture, heating value and gas concentrations was determined.
3. The examinations were conducted on practice scale storage piles (> 500 m³ each).
4. Coarse and fine chips showed comparable dry matter losses after 9-months storage.
5. Coarse wood chips dried faster than fine chips in the first 4 months of storage.

Introduction

Woody biomass from agriculture and forestry is one of the main sources for meeting global energy demand. On the basis of European objectives to increase energy supply from renewable sources to 20% of end energy consumption for the Member States of the EU by the year 2020, demand for wood will increase further in the coming years [EUROPEAN UNION, 2009]. In order to ensure regional supply with wood for energy use, fast-growing trees such as poplar and willow are already being cultivated in short rotation coppices (SRC) on over 32,000 ha in Europe [PECENKA ET AL., 2014]. The prerequisite for increasing acceptance of energy wood cultivation in agriculture, however, is not only the cost-efficiency of wood chip production, but also the availability of suitable technologies and competitiveness vis-à-vis other energy-supplying plants and traditional field crops [BERHONGARAY ET AL., 2013; ROSENQVIST ET AL., 2013; PECENKA & HOFFMANN, 2015]. The key problems currently facing expansion of SRC cultivation include insufficient availability of efficient harvesting machinery [SPINELLI ET AL., 2011; SCHWEIER & BECKER, 2012; EHLERT & PECENKA 2013; SPINELLI ET AL., 2014; SCHWEIER ET AL., 2015; VANBEVEREN ET AL., 2015] and high dry matter losses during the storage of wood chips [NOLL & JIRJIS, 2012; MANZONE ET AL., 2013; BARONTINI ET AL., 2014]. As in winter wood chips are harvested with a moisture content of 50 – 60%, they generally have to be placed in intermediate storage until the next heating season (for six to nine months). The different storage systems used so far can either only be managed with high technical expense (e.g. hot air drying, whole tree storage), or lead to high storage losses of up to 30% dry matter (e.g. in uncovered fine chip piles in the case of natural drying) that are reflected completely in cost-relevant energy losses and quality losses [GIGLER ET AL., 2000; GIGLER ET AL., 2004; SCHOLZ & IDLER, 2005; SCHOLZ & IDLER, 2007].

Examinations of the storage and drying behaviour of chips, chunks and whole trees have shown that the particle size of the material has an essential influence on moisture content and losses during storage over a period of six to twelve months [MITCHELL ET AL., 1988, GIGLER ET AL., 2004; JIRJIS, 2005, SCHOLZ & IDLER, 2007; HORVATH ET AL., 2012]. BARONTINI ET AL., 2014 and PECENKA ET AL., 2014 determined storage losses of 15 to 27% dry matter and moisture contents of 30 to 34% for the storage of fine chips (storage duration six to seven months). For the drying of willow chunks, GIGLER ET AL. (2004) determined storage losses of only 5% and moisture contents of 10% after storage in an open-air pile for five months. Studies on the storage of whole trees (poplar) have shown that storage losses can be reduced distinctly in comparison with those of fine chips (to approx. 7%), but with a moisture content of 41% after storage for 10 months [LENZ, 2011]. Mass losses are caused by physical, chemical and microbiological conversion processes leading to a significant temperature rise in a storage pile. According to PECENKA ET AL., 2014, BARONTINI ET AL., 2014

and MANZONE ET AL. 2013, when the different temperature profiles in wood chip piles are considered, two typical phases lasting over a relatively long period become visible:

- >50°C (high temperature phase)
- <30°C (low temperature phase)

Due to the homogenous raw material and bulk properties and the associated ease of handling and use, wood chips are preferred as a matter of principle for supplying automated heating boilers [STREHLER, 2000; JENSEN ET AL., 2004; WU ET AL., 2011]. Coarse chips produced with modern tractor-mounted mower-chippers [WIENEKE, 1993; EHLERT & PECENKA, 2013] have distinctly larger dimensions. On the one hand they satisfy the requirements made of bulk product properties for wood chip fuels in accordance with the standard DIN EN ISO 17225-4, and on the other hand – due to their coarse particle structure – they can show advantages regarding faster natural drying in storage piles coupled with reduced losses. Therefore the main objective of the current research project was to develop and perform a storage experiment in which the storage behaviour of fine and coarse chips could be examined and compared in detail over a period of nine months under practice scale conditions.

Material and methods

In the harvest season 2014, two storage piles with poplar chips of different chopping formats were established on a practical scale at the location Altentreptow, Germany (53°40'N; 13°13'E). In order to provide the necessary wood chips, two neighbouring poplar plantations (53°47'N; 13°14'E) were harvested with the clones Max 1, 3, 4 (*Populus nigra* x *P. maximowiczii*). Fine chips were produced from the four-year, double-row stand (first rotation). The coarse chips originated from a five-year single-row stand (first rotation). The harvest was carried out with two different continuously-working harvesting systems. In addition to a forage harvester with an SRC header (New Holland FR9060 with KUP 130), which produced the fine chips, the tractor-mounted mower-chipper (Fendt 820 Vario with ATB mower-chipper, Germany) produced coarse chips [EHLERT & PECENKA, 2013].

The harvesting and the storage intake of approx. 600 m³ coarse chip material were carried out on 31.01.2014 at a temperature of -5°C. The approx. 1000 m³ fine chips were harvested and taken into storage at a temperature of +4°C on 12.02.2014. Both storage piles were established next to each other on a concrete surface in a horizontal clamp silo (Figure 1.1).

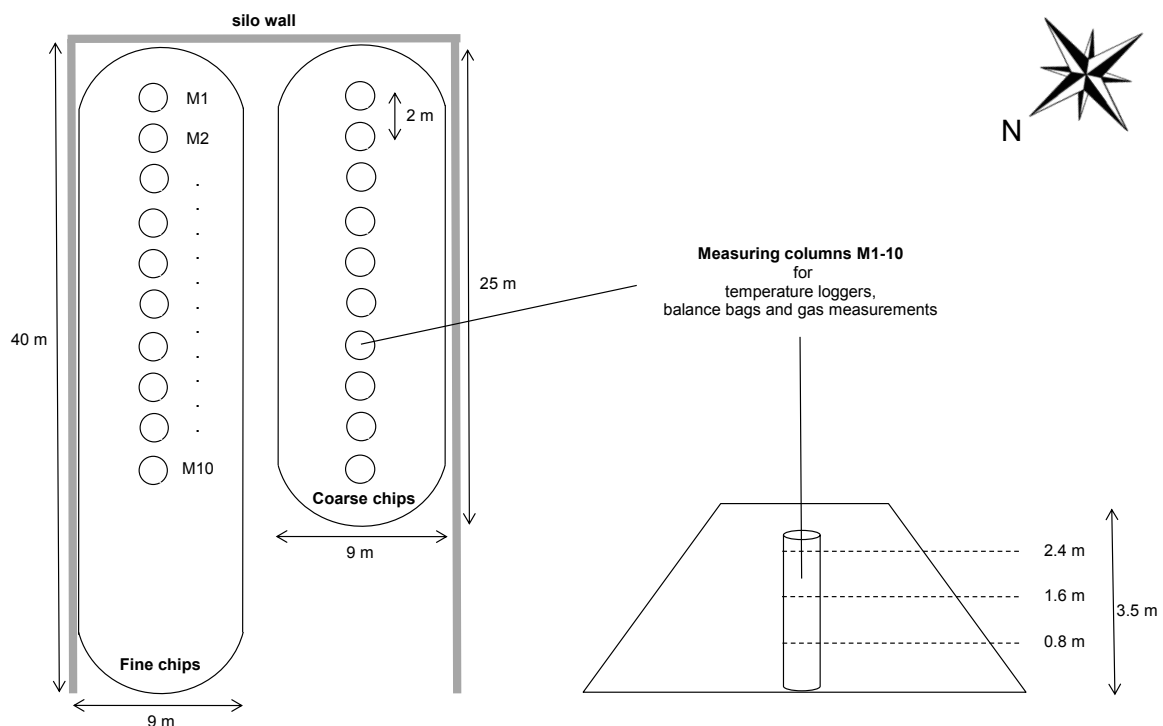


Fig. 1.1: Experimental set-up of two storage piles with poplar wood chips in a clamp silo with built-in stainless steel lattice columns for regular monitoring

In order to generate regularly measuring data over a nine-month storage period, ten stainless steel lattice columns (height 2.5 m, diameter 0.64 m, mesh aperture 20 mm) filled with the

respective wood chips were placed in each pile at intervals of 2 m centrally and lengthways to the storage heap direction during storage intake. The size and positioning of the lattice columns in relation to the size of the storage pile has been investigated in several pre-tests. Due to the chosen layout an influence of the extraction of a sampling column on the neighbouring columns can be virtually ruled out. Various measurements were conducted regularly at three different heights (0.8 m; 1.6 m; 2.4 m) (Figure 1.1). The measured values from these three levels have been combined to one measuring point to generate representative data a statistical evaluation of the storage process.

The two storage piles were covered with a semi-permeable non-woven fabric of type Toptex (mass 200 g m⁻², Tencate, Austria) that allows water vapour to leave the pile structure, but reduce the infiltration of precipitation.

The integrated lattice columns in each pile served to support the measurements and make it possible to withdraw wood chip samples completely without damage every four weeks (Figure 1.2). The wood chips samples have been attached inside and outside of the columns in balance bags (PP - plastic bags, mesh size 12 x 4.5 mm, sample mass 2 kg fresh material). After extracting a lattice column and removal of the balance bags the remaining wood chips from the column have been used to close the hole in the pile.



Fig. 1.2: Installation of sampling columns with balance bags during the storage intake of fine chips in a clamp silo

The chip formats were characterised with the help of an ultimate analysis (C, N, S, H, n = 5) on the ultimate analyser (Vario EL, Elementar, Germany) in accordance with VDLUFA, 1997 and the ash contents in accordance to DIN EN 14775 (n = 30). Both chip formats were distinguished and classified in accordance with DIN EN ISO 17225-4 (n = 7).

On each of the ten monthly sampling dates, one lattice column was removed from the storage pile and the following parameters were determined:

- Pile temperatures with the aid of temperature sensors (Gemini Type Tinytag TGP-4017, United Kingdom) at three heights with two sensors each
- Dry matter contents (n = 10 per level)
- Dry matter losses from balance bags (n = 10 per level)
- Higher and lower heating values (n = 3 per level)
- CO₂ and O₂ concentration (n = 1 per level)

These parameters were also measured for each type of wood chips on storage intake.

The dry matter content respectively moisture content were determined in accordance with the oven dry method [DIN EN 13183-1]. The losses were determined from the material in the balance bags. The dry matter losses (L) were calculated using the following Equation (1.1).

$$L = \left(1 - \frac{m_{out}(100 - x_{out})}{m_{in}(100 - x_{in})}\right) \times 100 \% \quad (1.1)$$

<i>L</i>	<i>dry matter loss</i>	<i>[%]</i>
<i>m_{in}</i>	<i>mass of material taken into storage on wet basis</i>	<i>[kg]</i>
<i>m_{out}</i>	<i>mass of material retrieved from storage on wet basis</i>	<i>[kg]</i>
<i>x_{in}</i>	<i>moisture content of the material taken into storage</i>	<i>[%]</i>
<i>x_{out}</i>	<i>moisture content of the material retrieved from storage</i>	<i>[%]</i>

For the energy evaluation, the higher heating value in accordance with DIN EN 14918:2014-08 was determined with the calorimeter C200 (IKA, Germany). The higher heating value of the water-free material (HHV) was calculated from the measured calorific heating value, the ash content and the elements carbon, hydrogen and sulphur from the ultimate analysis in accordance with Equation (1.2).

$$HHV = q_{v,gr,d} - [k \times H + 0.8 \times (100 - x - ash - C - H - S)] \quad (1.2)$$

<i>HHV</i>	<i>higher heating value at constant pressure on water-free reference basis</i>	<i>[MJ kg⁻¹]</i>
<i>q_{v,gr,d}</i>	<i>calorific value at constant volume on water-free reference basis</i>	<i>[MJ kg⁻¹]</i>

<i>k</i>	<i>evaporation heat including the volume work of the water formed from the hydrogen during combustion at 25°C (0.2122)</i>	<i>[MJ %_H⁻¹]</i>
<i>H</i>	<i>hydrogen content of the fuel on water-free reference basis</i>	<i>[%]</i>
<i>x</i>	<i>moisture of the fuel in analysis on water-free reference basis</i>	<i>[%]</i>
<i>ash</i>	<i>ash content of the fuel on water-free reference basis</i>	<i>[%]</i>
<i>C</i>	<i>carbon content of the fuel on water-free reference basis</i>	<i>[%]</i>
<i>S</i>	<i>sulphur content of the fuel on water-free reference basis</i>	<i>[%]</i>

Taking the enthalpy of evaporation of water into account, the lower heating value (LHV, on wet basis) was calculated from the HHV using Equation (1.3).

$$LHV = \frac{HHV \times (100 - x) - \Delta Q_v \times w}{100} \quad (1.3)$$

<i>LHV</i>	<i>lower heating value (on wet basis)</i>	<i>[MJ kg⁻¹]</i>
<i>HHV</i>	<i>higher heating value at constant pressure on water-free reference basis</i>	<i>[MJ kg⁻¹]</i>
<i>x</i>	<i>moisture content of the fuel</i>	<i>[%]</i>
ΔQ_v	<i>evaporation enthalpy of the water (2.441)</i>	<i>[MJ kg⁻¹]</i>
<i>w</i>	<i>moisture of the fuel in analysis on water-free reference basis</i>	<i>[%]</i>

The heating value of mass on wet basis taking storage losses into account is defined here additionally as specific heating value (SHV) (Eq. (1.4)).

$$SHV = \frac{m_{out}}{m_{in}} \times LHV_{out} \quad (1.4)$$

<i>SHV</i>	<i>specific heating value</i>	<i>[MJ kg⁻¹]</i>
<i>m_{out}</i>	<i>mass of the material retrieved from storage</i>	<i>[kg]</i>
<i>LHV_{out}</i>	<i>lower heating value of mass on wet basis retrieved from storage</i>	<i>[MJ kg⁻¹]</i>
<i>m_{in}</i>	<i>mass of the material taken into storage</i>	<i>[kg]</i>

In order to be able to draw conclusions concerning conversion processes within the piles, the O₂ and CO₂ concentrations (n = 1) were determined with the photoacoustic gas measuring device (Model 1312, Innova AirTech Instruments, Germany) right before each removal of one of the sampling columns at three levels (0.8 m, 1.6 m and 2.4 m, see Figure 1.1). Gas concentrations are not only an indicator for chemical and microbiological degradation processes. Furthermore, a shortage of O₂ together with high temperatures could slow down fungi growth leading to reduce dry matter losses. Furthermore, it should be investigated if the different pile porosities due to different chip sizes have any influence on gas exchange between pile and ambient air.

During the clearing of the piles at the end of the storage period on 26.10.2014 a moisture profile (n = 26) from each pile was determined in a double evaluation over the entire cross-section in order to assess the outer spoilage layer (Figure 1.3).

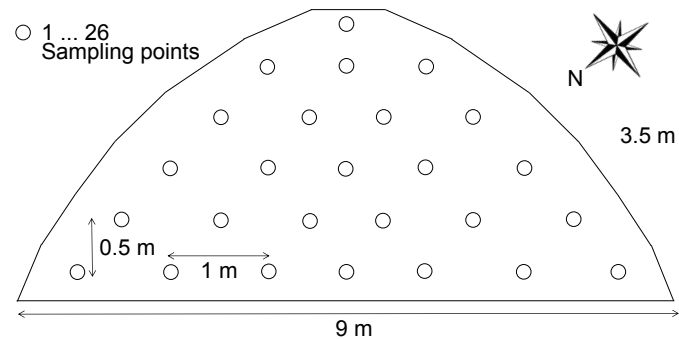


Fig. 1.3: Distribution of sampling points over the pile cross-section during the clearing of each pile at the end of the storage period

Weather data such as outdoor temperature, relative atmospheric humidity and precipitation were obtained from the Trollenhagen weather station of the German Meteorological Service (Deutscher Wetterdienst) (53°36'N; 13°19'E) during the whole experiment.

For the statistical evaluation of the dry matter losses and moisture contents of both chip formats during storage, a bi-factorial generalised linear model (month, chip format) was used and a binomial distribution was taken as a basis. In addition, a logit link function ensured that the values predicted with the model are only issued between 0 and 1 (SAS Version 9.3, SAS Institute Inc., USA).

Results

Quality of the wood chips

The results of the characterisation of the material properties of the two kinds of wood chips before the start of the storage period are listed in Table 1.1. The moisture contents and the element contents are in a comparable range for both chip formats.

Tab. 1.1: Material properties of two kinds of poplar chips before the start of the storage period

Parameter	Moisture content	Bulk density	Ash	Elements			
				H	C	N	S
	%	kg _{wb} m ⁻³	%	%	%	%	%
Fine chips	59.9 ($\sigma \pm 0,7$)	351 ($\sigma \pm 14$)	2.07 ($\sigma \pm 0,22$)	7.26 ($\sigma \pm 0,61$)	50.95 ($\sigma \pm 0,53$)	0.39 ($\sigma \pm 0,29$)	0.08 ($\sigma \pm 0,01$)
Coarse chips	58.5 ($\sigma \pm 1,0$)	341 ($\sigma \pm 22$)	1.49 ($\sigma \pm 0,21$)	7.43 ($\sigma \pm 0,62$)	51.48 ($\sigma \pm 0,50$)	0.29 ($\sigma \pm 0,20$)	0.11 ($\sigma \pm 0,02$)

wb ... on wet basis

Particle size analysis

The results of the particle size analysis before the start of the storage period classify the fine chips in the group of P31 and the coarse chips in the group of P45 (Figure 1.4).

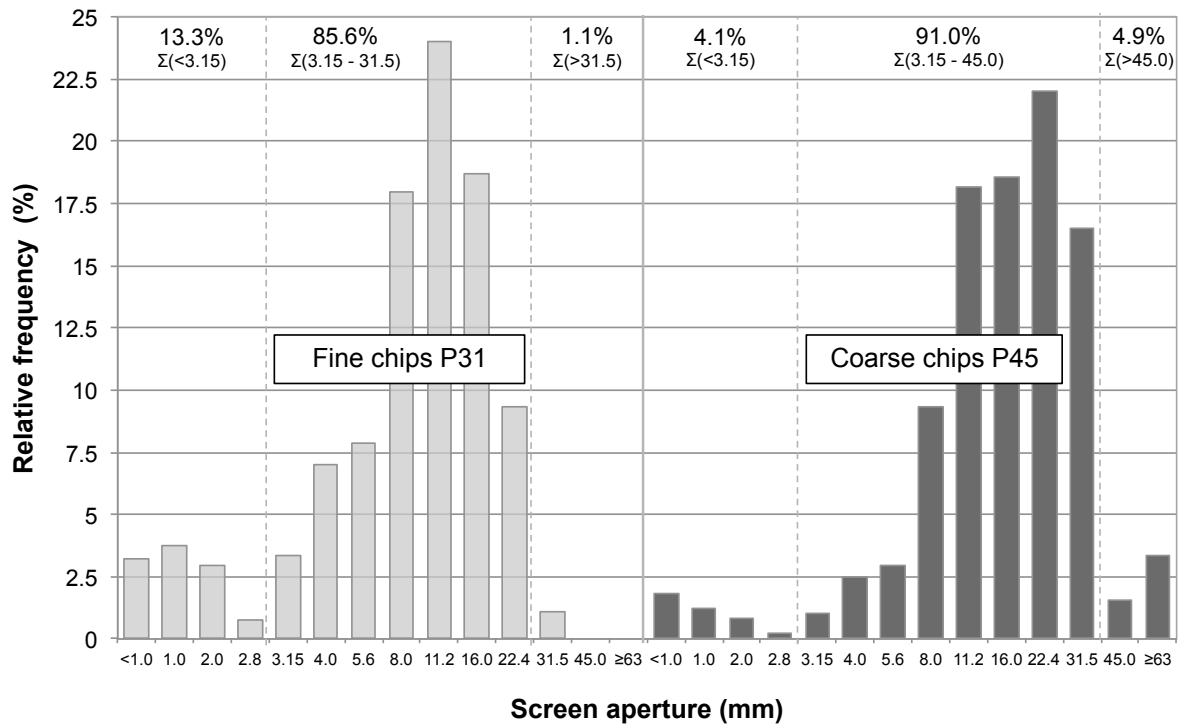


Fig. 1.4: Particle size analysis of the fine and coarse chips before the start of the storage period

It is conspicuous that the P31 (fine chips) exceed the admissible upper limit of the fines of 10% by 3.3 percentage points and in theory do not comply with the standard. The novel harvesting principle of the ATB mower-chipper produces wood chips more selectively in one fraction size class and with a very low share of fines. Despite this, both wood chip formats satisfy the minimum limit of the main fraction, which must represent over 60% on a pro-rated basis [DIN EN ISO 17225-4].

Storage pile temperatures

The strong increases in temperatures that started directly within a short period after a temperature of 0°C in the piles was exceeded were characteristic for both piles (Figure 1.5).

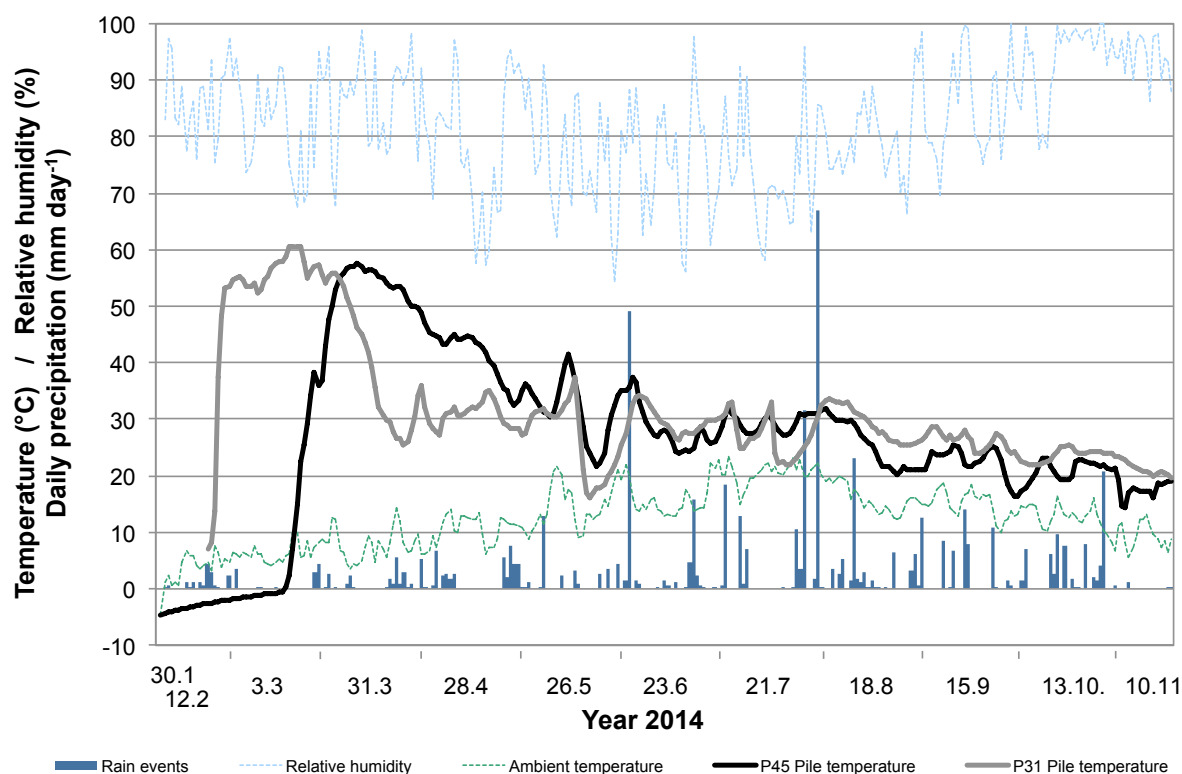


Fig. 1.5: Weather conditions and in-pile temperatures during nine months storage of fine (P31) and coarse (P45) wood chips

The increases of in-pile temperature reached their maximum value at 61°C (P31, fine chips) and 58°C (P45, coarse chips). The temperature in the P31 pile rose directly after storage intake to over 50°C (high temperature phase). This phase lasted for 36 days. While in the P45 pile the temperature rise did not start until after approx. five weeks, the high temperature phase only lasted for 22 days. At the end of the high temperature phase, when the temperature dropped to values lower than 50°C in the fine/coarse chip pile, both pile temperatures approximate gradually to the outdoor temperature in different time periods. Following a temperature transition of 10 days, the temperature in the P31 pile reached temperatures below 30°C (low temperature phase) apart from a few short exceptions. The P45 pile on the other hand required 48 days for this. After that the temperatures in the piles followed the outdoor temperature fluctuations, but at an approx. 10°C higher level. Heavier precipitation and strong outdoor temperature drops resulted in general in a reduction in pile temperatures.

Gas measurements

The results of the gas measurements from the three levels (0.8 m, 1.6 m and 2.4 m, Figure 1.1) showed that higher CO₂ and low O₂ concentrations prevail in particular in the respective high temperature phases (P31: 18.2. – 25.03.2014; P45: 20.03. – 10.04.2014) (Figure 1.6).

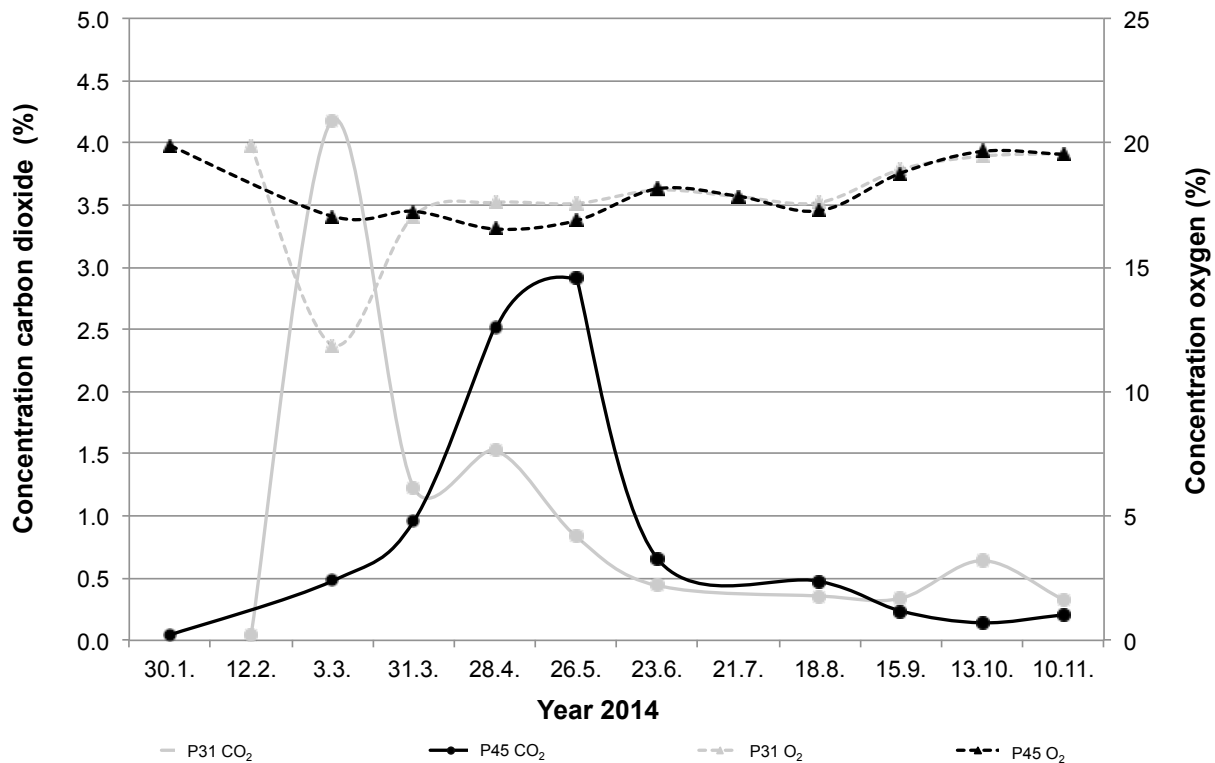


Fig. 1.6: O₂ and CO₂ concentrations in the piles during storage of fine (P31) and coarse wood chips (P45)

The pile of fine chips reached its highest CO₂ mean value of 4.2% and its lowest O₂ mean value of 11.9% after a storage period of two months on 03.03.2014. According to this result – as expected – the CO₂ concentration correlates negatively with the O₂ concentration. In contrast to this, the coarse chips reached their peak in mean CO₂ concentration after a storage period of four months (26.05.2014) at just 2.9%, with an O₂ concentration of still 16.9%. For both chip sizes the increase in CO₂ concentration occurred simultaneously to the increase in temperature. This method of periodical gas measurement inside a storage pile has been tested at this experimental setup for the first time. Due to the low number of independent measurements (n = 1 per level) no statistical analysis has been done.

Dry matter losses

Both the changes in moisture content and the dry matter losses of the two chip formats differ during the storage (Figure 1.7). Before the dry matter losses of both formats reached their plateau between 17 and 22% after four to five months (26.05.2014), they rose quite linearly. As the statistical data analysis has shown, there are, however, no significant differences between P31 and P45 as regards the development of the dry matter losses across the entire storage period (p = 0.8896). Accordingly the chip format showed no statistical influence on the dry matter losses.

As of 26.05.2014, both chip formats show a significant difference over the storage period ($p = 0.0164$) compared to the beginning of the storage period. After a total storage period of approx. nine months, dry matter losses of 22% for fine chips ($\sigma \pm 2.9$) and 21% for coarse chips ($\sigma \pm 3.3$) were determined.

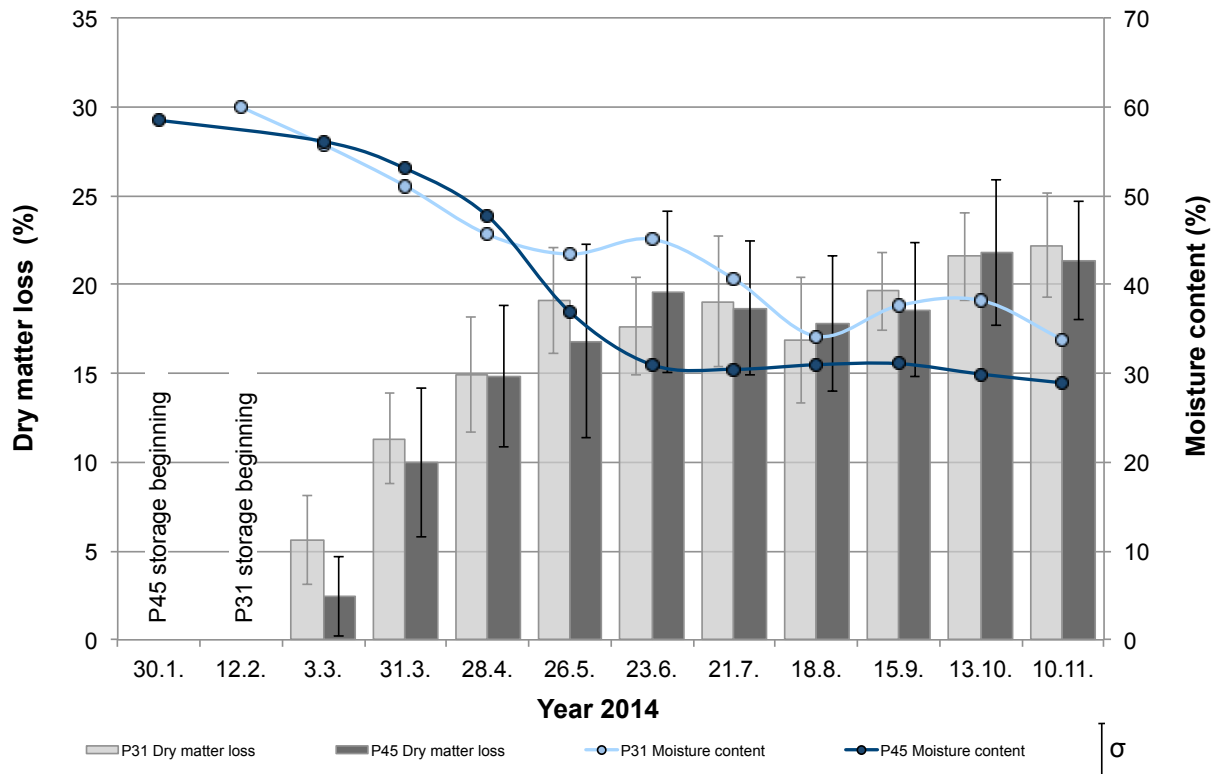


Fig. 1.7: Dry matter losses and moisture contents of fine (P31) and coarse wood chips (P45) during the entire storage period

Moisture contents

On storage intake, the moisture content of P31 was 59.9% ($\sigma \pm 0.7$) and that of P45 was 58.5% ($\sigma \pm 1.0$). After a storage period of seven months, the P31 still had a moisture content of 34.2% ($\sigma \pm 3.8$), while the P45 reached this moisture content (31.0%, $\sigma \pm 8.6$) already after five months. At the end of the storage period, the average moisture content of P31 in the measuring column was 33.8% ($\sigma \pm 5.3$), respectively 28.9% ($\sigma \pm 6.4$) for P45. The distribution of the moisture contents at the end of the storage period revealed for both piles non-homogenous drying conditions (Figure 1.8).

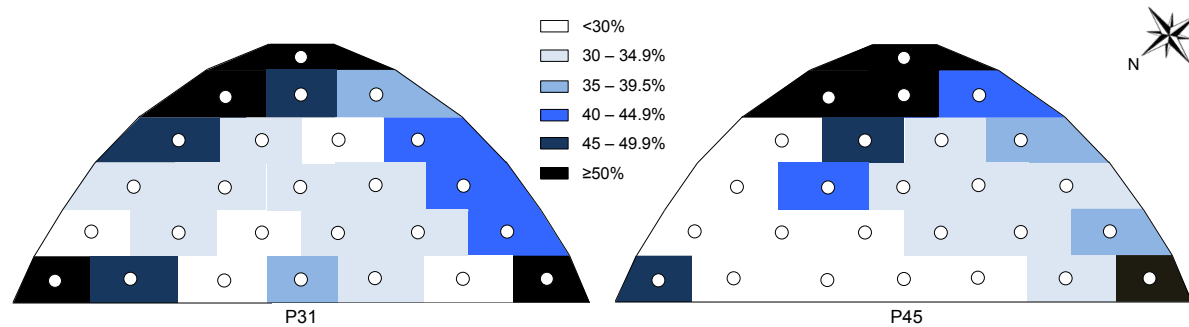


Fig. 1.8: Distribution of the moisture contents of fine (P31) and coarse wood chips (P45) across the pile cross-sections at the end of the storage period on 26.11.2014

The moisture content distribution in both storage piles shows clearly that both piles are dryer on the inside than on the outside. In the case of the fine chips, the moisture contents fluctuated between a minimum of 27.0% in the core and a maximum of 77.2% in the peripheral areas (10 – 30 cm thick). On the pile ridge (60 cm thick), the damp peripheral zones were deeper than at the pile edges. The mean value for the entire cross-section for all P31 samples was 38.7% ($\sigma \pm 11.1$). The values of the moisture cross-section determination for the coarse chips vary more strongly. They fluctuate between a minimum of 19.8% and a maximum of 77.3%. Despite of this higher variation coarse chips are with an average moisture content of 36.6% ($\sigma \pm 13.8$) only 2 %-points dryer than fine chips. The peripheral zone at the pile ridge measures 70 cm, and that at the pile edges only 5 – 20 cm.

According to the statistical data analysis, there is no significant difference between the coarse and fine chips regarding the change in moisture content over the entire storage period ($p = 0.7272$). The chip format thus does have any statistical influence on the drying. However, a comparison of the timeframe shows significant differences recorded as of 23.06.2014 ($p = 0.0031$).

Heating values

Alongside the moisture contents and dry matter losses, the lower heating values belong to the most important economic performance indicators of wood chips. The comparison of the three different calorific values of both chip formats shows that the moisture content and the dry matter losses have a substantial influence on the energy value of the materials in storage (Figure 1.9).

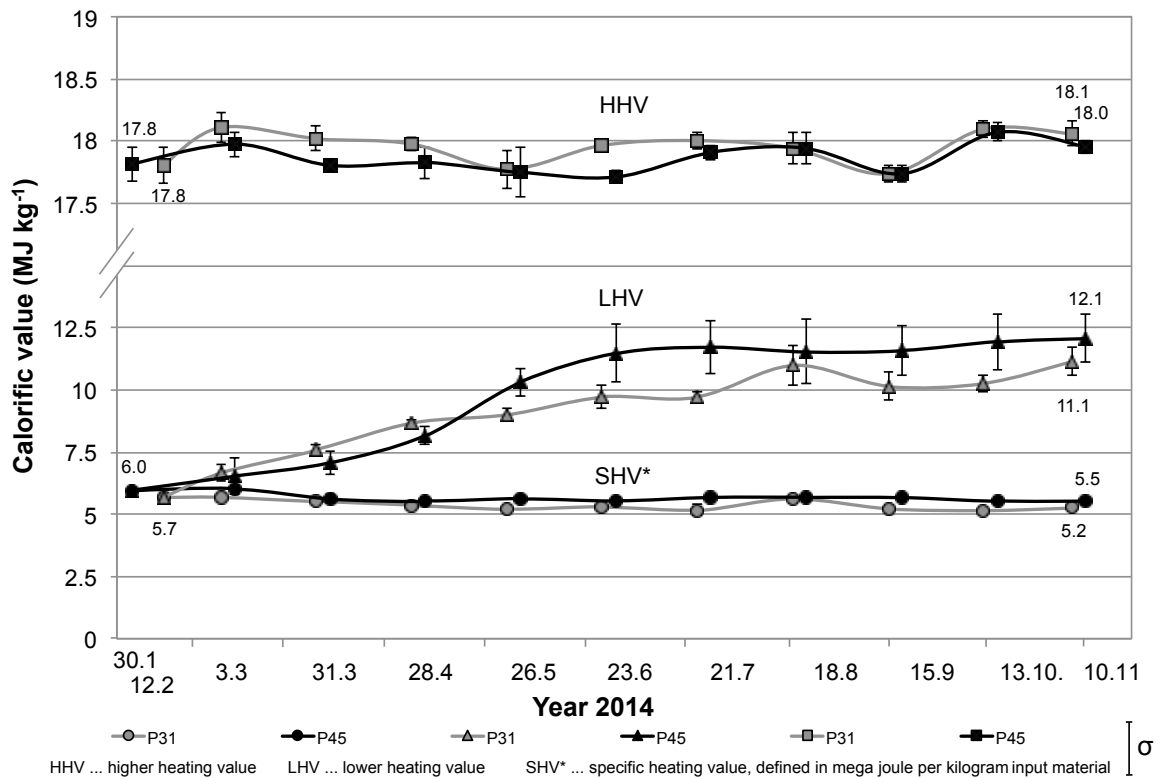


Fig. 1.9: Development of higher, lower and specific heating values for fine (P31) and coarse wood chips (P45) during a nine-month storage period

The HHV varies very little independently of the chip format and on average is at a stable level between 17.7 and 18.1 MJ kg⁻¹. If the LHV is considered, which takes the moisture content of the material into account, the energy value of both chip formats doubles until the end of the storage period. According to the statistical analysis, there are no significant differences between fine and coarse chips regarding the HHV and LHV ($p_{\text{HHV}} = 0.0895$, $p_{\text{LHV}} = 0.5027$). The SHV includes the developing storage losses and the drying during the storage period. Taking this into account, there is a significant difference for the SHV between fine and coarse chips ($p = 0.0020$). In both chip formats the SHV drops by 0.5 MJ kg⁻¹ (approx. 10%).

Discussion

The main objective of the current research project was to develop and perform a storage experiment in which the storage behaviour of fine and coarse wood chips could be examined and compared in detail over a period of nine months.

The temperature profile is a key factor influencing the physical, chemical and microbiological conversion processes, and at the same time an indicator of what is going on in the pile during storage. The conducted storage experiment showed that the strong increase of the temperature in each of the two storage piles with fine/coarse wood chips started always when exceeding a temperature of 0°C inside the pile independently of the length of the time period after starting the storage process. Furthermore, independently of the chip format, the start of this strong increase in in-pile-temperature depends on the outdoor temperatures at the time right before storage intake and on the gradual rise of the pile temperature during rising outdoor temperatures. The coarse chips in this experiment were taken into storage at -5°C and remained in frozen condition for about five weeks. As long as a pile is frozen, no conversion processes occur and the storage stability is largely retained. This is confirmed by findings of earlier practical tests [PECENKA ET AL., 2014]. Here too, the pile temperature of coarse chips remained below 0°C for over five weeks following storage intake at -12°C. In contrast to this, the fine chips were harvested at temperatures above freezing point and the temperature within the pile began to rise immediately (three weeks before P45).

The first rise in temperature is triggered initially by the residual respiration of those wood cells that are not dead [MITCHELL ET AL., 1988; KALTSCHMITT ET AL., 2009]. In the P45, the share of dry matter losses attributable to this residual respiration only becomes visible on 31.03.2014 following eight weeks of storage, as the material was still frozen on the preceding measuring date (Figure 1.6). In the P31, higher dry matter losses can be seen already on 03.03.2014.

The strong rise in temperature inside the storage piles creates favourable conditions for the development of microorganisms and at the same time accelerates chemical conversion processes [FERRERO ET AL., 2009; FERRERO ET AL., 2011]. The resulting moist and warm environment provides a suitable habitat for both bacteria and fungi. The maximum pile temperatures only slightly exceeded 60°C and support the statement that fungi make an essential contribution to the temperature increase. Respiratory products of fungi are CO₂ and H₂O. A shortage of O₂ together with high temperatures could slow down fungi growth. According to the measurements this could take place especially in the P31 pile. However, with a minimum O₂ concentration of 12% (P31) the effect on fungi growth is probably very limited. A direct cause for the measured differences in course in time of in-pile gas concentrations has to be seen in the significant differences in the particle size distribution of fine and coarse chips. The higher porosity of the coarse chip pile allows a much faster gas

exchange between pile and ambient air. As a consequence, the P45 pile was supplied continuously with oxygen throughout the entire storage period. Aerobic decomposition processes therefore encounter more favourable conditions here. At the same time the smaller surface area of the P45 restricts decomposition processes, so that altogether there were no significant differences between fine and coarse chips in the development of dry matter losses.

Despite differing pile temperature profiles of the different chip formats, the developments of the dry matter losses displayed a similar curve. The strong increase in dry matter losses ends in both piles already after approx. four months of storage on 26.05.2014. Readily available nutrients have presumably largely been used up by this time. At the same time the storage pile moves into the low-temperature phase. It can be derived from this that a substantial portion of dry matter losses in the case of the P45 occurred at temperatures of $>30^{\circ}\text{C}$ in the presence of sufficient moisture. Compared to this the dry matter losses in the P31 were only 11% on 31.03.2014, although the pile temperature had already dropped to around 30°C . There are different species of fungi which have their optimum growth temperatures either at the high temperature level of $50 - 60^{\circ}\text{C}$ or at a lower level around 30°C , all actively degrading wood chips. Accordingly it is not possible to conclude only from the temperature profile how the dry matter losses of each chip format proceed. Differences in dry matter losses may also have been caused by a high bark component [BOJANA ET AL., 2002]. This would ensure improved nutrient availability and conversion. The younger stand in the case of the fine chip coppice and the double-row plantation spacing led to thinner shoots forming in the felled area. This could explain the significant higher ash level of the P31 by comparison with the P45 ($p = 0.0007$).

Diverse chemical processes such as oxidation and hydrolysis of carbohydrates also proceed in varying intensities and at different speeds during the high temperature phase. This results in a dry matter loss, though the interactions between and the quantity of individual decomposition processes (residual respiration, fungi growth and chemical conversion) are not yet clarified.

After storage for 3 – 4 months, the pile temperatures approximate to the outdoor temperature, which results in an only marginal increase of dry matter losses. The weather situation also influences the changes in quality properties throughout the entire storage period. For example the dry spring in 2014 had a very positive effect on the results in the form of rapid drying progress with relatively low dry matter losses. Comparative studies underpin the fact that in the case of unfavourable weather conditions, the dry matter losses can rise to levels of 25 – 30% [PECENKA ET AL., 2014].

One significant difference between the two chip formats is that the coarse chips can be used efficiently as fuel already after five months, with moisture content levels of around 30%. This reduces storage and capital commitment costs.

Conclusions

The investigations have shown that there are differences between coarse and fine wood chips regarding drying behaviour during storage. Despite this, these are not statistically significant.

Considering the energy aspects, it was established that the declining moisture contents during storage have a positive effect, but that the resulting parallel storage losses occurring largely cancel out this advantage. In future studies it should be examined whether there are any significant differences between the storage of wood chips over 100 mm in length and the storage of fine chips. Gas measurements were conducted for the first time in real-life piles in order to be able to allocate shares in the losses to individual processes. Clear differences in CO₂ and O₂ concentrations between fine and coarse wood chips have been observed.

Consequently more detailed gas measurements in wood chip piles comparing fine, coarse and very coarse chips (>100 mm in length) with focus on the influence of gas permeability are recommended. Connected with chemical analyses of the chips within the high temperature phase such experiments could describe and hopefully explain the interactions and relations between the individual conversion processes.

Differences in dry matter losses may also have been caused by different bark contents of fine and coarse wood chips investigated in this experiment. Further studies are necessary to clarify to what extent the bark component, the active surface and the aeration within the pile can influence the course of storage. Furthermore detailed gas measurements should be conducted on a model basis to quantify the causes of losses, so that optimal storage conditions can be created.

Mass losses have been measured in the lattice columns only. The data was appropriate for the comparison of fine and coarse chips but not for the evaluation of the whole storage pile.

In the peripheral wet areas of a chip pile, the high moisture contents and the moderate temperature levels will facilitate the growth of fungi leading to much higher dry matter losses. However, monthly measurements of storage losses in the whole pile profile are important for a better understanding of storage processes but they are very labour intensive and require much higher amounts of wood chips than currently regionally available in Germany.

Harvesting during frost conditions is recommended in order to prolong the storage stability of the chips without sustaining losses. The advantage of coarse chips over fine chips is primarily that they dry off faster. This circumstance in turn has a positive effect on the lower and specific heating value, which reflects the monetary value of the material.

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Chapter two

Development and test of a simplified method to calculate dry matter loss during open-air storage of poplar wood chips by analysing ash contents

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Abstract

Short rotation coppice (SRC) in agriculture can be established successfully, only if the entire process chain is economically competitive. Despite the substantial dry matter loss (up to 25%) occurring during open-air storage of wood chips, it is the most applied storage technique. Since the particle size of wood chips plays an important role in storage and drying processes, two storage piles ($> 500 \text{ m}^3$) with fine and coarse wood chips were investigated comprehensively under the weather conditions of North-East-Germany over a period of 9 months.

The objective of this experiment was to develop a simplified method to calculate dry matter loss by determining the ash content and to compare the results with the conventional sample bag method. The new method delivered statistically sound results, particularly when ash contents were calculated from separated bark and wood samples instead of from wood chip samples. Furthermore, the significant and consistent increase in ash content of the bark samples during storage suggests, that the development of a model solely based on ash content of separated bark could be advantageous in terms of simplified yet reliable determination of dry matter losses. Since the ash content of wood chips is largely governed by the bark content, exact data for the proportion of bark is required, which varies between 18 and 35% depending on tree size represented by the stem diameter at cutting height (SDCH). Moreover, it was found that the fuel quality depends more on the SDCH of the SRC-harvest than on the produced wood chip format.

Keywords

Short rotation coppice, wood chips, storage, ash content, dry matter loss calculation

Highlights

1. Storage characteristics for fine and coarse wood chips from poplar were investigated over a period of 9 months.
2. The investigations were carried out in typical practice size storage piles ($> 500 \text{ m}^3$ per pile).
3. The correlation between mass losses and ash contents were analysed in detail.
4. The ash content of wood chips is mainly determined by the stem base diameter of the trees at harvest.
5. A simplified method has been developed to calculate dry matter losses by means of ash content changes during storage.

Introduction

Cultivating short rotation coppice on arable land offers the opportunity to produce biomass sustainably, while improving the agricultural earnings. Under European conditions, fast growing trees like poplar (*Populus* sp.), willow (*Salix viminalis*) and robinia (*Robinia pseudoacacia* L.) cultivated in short rotation coppice or agroforestry systems have the potential of producing more than $10 \text{ t ha}^{-1} \text{ yr}^{-1}$ of plant biomass (dry matter) [SCHOLZ ET AL., 2011; BENETKA ET AL., 2014; LARSEN ET AL., 2014]. The wood produced on such land is either preferably utilised for the heat generation in farm-owned facilities or sold as fuel to regional heating (power) plants. However, in order to increase the acceptance of cultivating fuel wood in agriculture, ensuring the quality of the produced wood chips is a prerequisite alongside the economic efficiency of wood production and the availability of suitable technologies for cultivation, harvest, and storage. Since wood chips are harvested in winter with moisture contents of up to 60% (defined as moisture mass fraction or moisture content on the wet basis), they must initially be dried and stored until the next heating season. Storage in the form of open-air piles facilitates a cost-efficient natural drying process, albeit leading to high dry matter losses up to 30% (defined as mass fraction on the dry basis) [NOLL & JIRJIS, 2012; MANZONE ET AL., 2013; BARONTINI ET AL., 2014; PECENKA ET AL., 2014]. These losses cause cost-relevant drawbacks not only in terms of energy, but also quality [MITCHELL ET AL., 1988; GIGLER ET AL., 2000; SCHOLZ & IDLER, 2007; NOLL ET AL., 2010]. Previous investigations have shown that particle size has a significant impact on storage and ventilation characteristics [JIRJIS, 2005; PECENKA ET AL., 2014; LENZ ET AL., 2015]. Fine poplar wood chips with dry matter losses ranging from 13 to 27% and moisture contents ranging from 30 to 34% demonstrated clearly inferior storage characteristics after a storage time of 6 to 7 months than coarse willow wood chips [BARONTINI ET AL., 2014; PECENKA ET AL., 2014; PARI ET AL., 2016]. GIGLER ET AL., 2004 have determined storage losses of only 5 %_{db} and 10%_{db} moisture contents after 5-months storage of willow wood chips in open-air piles. Depending on mass loss during drying, energy losses of up to 14% may occur. At the same time, the ash content increases during storage due to the reduction of organic components by approximately 1 percentage point [PARI ET AL., 2015]. High bark contents in the crop mass resulting in high ash content may hence lead to exceeding the limit of 3% ash for wood chips, as stipulated in the EN ISO 17225-4 fuel standard.

The efficient and trouble-free operation of biomass fired heating (power) plants requires exact knowledge about storage characteristics of wood chip piles as well as the fuel parameters such as particle size, moisture content, heating value, and ash content. LENZ ET AL. (2015) presented a comprehensive storage test comparing the storage behaviour of fine (P31) and coarse (P45) wood chips from poplar. The experiment was designed to monitor the continuously changing mass losses, moisture contents, heating values, and ash contents

during 9-months storage under the weather conditions of North-East-Germany. The investigation was conducted on practice scale storage piles ($> 500 \text{ m}^3$). The continuous determination of mass losses by means of the commonly used sample bag method was fairly troublesome, particularly when measurements had to be performed over a long period of time. Furthermore, the inversely proportional relationship between the ash contents and the content of organic components might be utilized as a basis for the indirect determination of mass losses during storage [BARONTINI ET AL., 2014; GEJDOS ET AL., 2015]. Therefore, the main focus of the research work lies on analysing the relationship between ash content and the progression of mass losses, with the objective of developing a simple and reliable method to calculate the dry matter losses. The developed model is then validated by comparing the results with the conventional sample bag method, which serves as a reference.

Material and Methods

Experimental set-up

In January 2014, two neighbouring poplar plantations (clones Max 1, 3, 4) located in west Mecklenburg Pomerania (North-East-Germany, 53°40'N; 13°13'E) were harvested by two different systems (each first rotation) and the produced wood chips were stored on a concrete surface (53°47'N; 13°14'E) for 9 months (Table 2.1). Fine wood chips (P31) were produced by employing a modified standard forage harvester with coppice header, while for the coarse wood chips (P45) the ATB mower-chipper [EHLERT & PECENKA, 2013; PECENKA ET AL., 2014] was used.

Tab. 2.1: Origin and harvest of wood chips for storage

Plantation (Layout)	Age	Harvest	Harvesting system	Chip format	Stem diameter at cutting height of 10 cm (SDCH)
m	Years	Date			cm
double row (2.2 x 0.5 x 0.6)*	4	12-02-2014	New Holland forage harvester, FR 9060 with 130 FB coppice header	fine wood chips (P31)	4.3 ($\sigma \pm 1.3$)
single row (2 x 0.6)**	5	31-01-2014	Fendt 820 Vario with tractor mounted ATB mower- chipper	coarse wood chips (P45)	7.1 ($\sigma \pm 1.4$)

* (row distance x inner row distance x planting distance); ** (row distance x planting distance);

In a bunker silo, 2 adjacent piles, one 1000 m³ pile of fine wood chips (pile dimensions: 40 m x 9 m x 3.5 m) and a 600 m³ pile of coarse wood chips (pile dimensions: 25 m x 9 m x 3.5 m), were stored in farm typical fashion. Further details of the experimental set-up and the results regarding the differences in the storage behaviour between fine and coarse chips in terms of moisture content, dry matter losses, gas concentrations, and changes in calorific value during this storage experiment were reported by LENZ ET AL. (2015).

Sampling

For continuous sampling over 9 months, ten stainless steel built grit columns ($t_1 - t_{10}$) filled with wood chips were positioned along the central axis every 2 metres (Figure 2.1). The height, diameter and mesh size of the grit columns were 2.5 m, 0.64 m and 20 mm respectively.

Every month, one grit column from each pile including the sample bags previously positioned on three different levels (0.8 m, 1.6 m, 2.4 m) was retrieved with a pulley and examined. The extraction spaces of the samples were refilled subsequently with the respective materials.

The grit columns contained sample bags with three different types of material:

1. Chips with the natural proportions of wood and bark;
2. Bark;
3. Wood without bark.

On each level, 6 sample bags filled with chips were positioned inside the column, while four additional sample bags were mounted outside the column (Figure 2.1). Moreover, one sample bag filled with bark, and wood without bark was positioned inside the column on the middle level. Manually decorticated trees served as the source of these separated bag contents. The lower and upper level contained exclusively sample bags filled with chips.

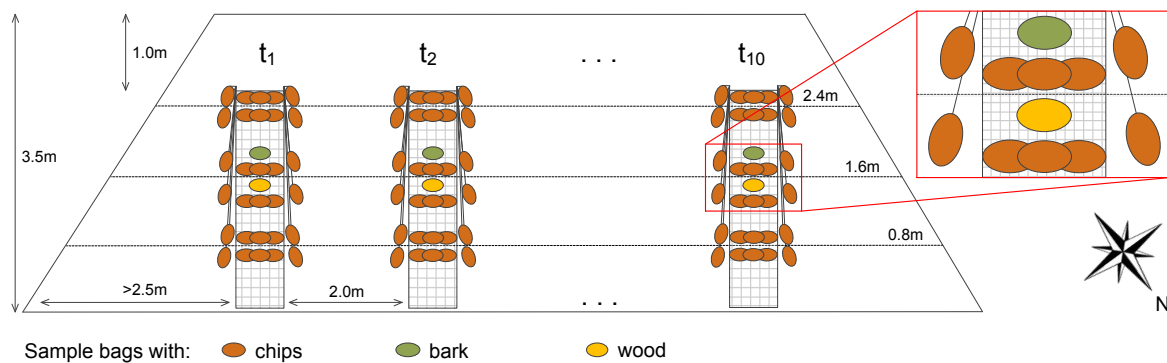


Fig. 2.1: Trial design for material sampling from the wood chips piles

The stored sample bags allowed the measurement of investigated parameters, which were recorded and analysed at regular intervals of 4 weeks over the entire storage period of 9 months (Table 2.2).

Tab. 2.2: Investigated parameters

Parameter	Unit	Storage per pile	Sampling per level	Methodology
Particle size distribution	%	n = 7	-	Association to EN ISO 17225-1
Moisture content	%	n = 60	n = 10	EN 14774-2
Gross calorific value	MJ kg ⁻¹	n = 30	n = 9	EN 14918
Ash content	%			EN 14775
chips		n = 30	n = 3	
wood and bark		n = 9	n = 9	
Dry matter loss	%			
sample bag		-	n = 10	equation 2.1
ash content		-	n = 30	equation 2.3
SDCH	cm	n = 60	-	sliding calliper
Branch content	% _{db}	n = 4	-	in-house method
Bark content of trees with SDCH:	% _{db}			in-house method
3 cm		n = 2	-	
6 cm		n = 2	-	
11 cm		n = 2	-	
15 cm		n = 1	-	
19 cm		n = 1	-	
Weather conditions				weather station Trollenhagen of the German Weather Service (53°36'N; 13°19'O)
outside temperature	°C			
precipitation	mm	-	-	
relative humidity	%			

SDCH ... Stem diameter at cutting height (10 cm), db = on dry basis

Reference method for determination of dry matter loss

The calculation of dry matter loss by means of sample bag method was used as reference. According to this method dry matter loss at any storage time, i can be calculated using the Equation 2.1.

$$L_{(sb) i} = \left(1 - \frac{m_i (100 - x_i)}{m_{in} (100 - x_{in})}\right) \times 100 \% \quad (2.1)$$

$L_{(sb) i}$	dry matter loss via sample bags at time, i	[%]
m_{in}	mass of in-column materials at storage start on wet basis	[kg]
m_i	mass of ex-column materials at time, i on wet basis	[kg]
x_{in}	moisture content of in-column materials at storage start	[%]
x_i	moisture content of ex-column materials at time, i	[%]

Determination of dry matter loss by ash content

Mass losses are caused solely by reduction of organic material. The absolute mass of inorganic matter in a wood chip sample, on the other hand, remains unchanged. Since the inorganic proportion is represented by the ash content, the reducing mass inevitably results in increasing ash contents relative to the dry mass of a sample. The relationship between dry matter loss and the change of ash content during storage at a certain time, i is described by Equation 2.2.

$$L_{(ash) i} = 1 - \left(\frac{ash_{in}}{ash_i} \right) \times 100 \% \quad (2.2)$$

$L_{(ash) i}$	<i>dry matter loss via ash content at time, i</i>	<i>[%]</i>
ash_{in}	<i>ash content at storage start</i>	<i>[%]</i>
ash_i	<i>ash content at time, i</i>	<i>[%]</i>

Harvested wood exhibits different wood-bark-ratios depending on location, tree type, and age [BOJANA ET AL., 2002; AMTHAUER & SEYMOUR, 2011], besides the ash content of bark is clearly higher than that of wood [KALTSCHMITT ET AL., 2009]. Since the samples for the determination of the ash content in wood chips are usually mixed samples with a heavily varying and random wood-bark-ratio, either many single samples must be examined followed by proper statistical evaluation or exact data of the corresponding wood-bark-ratio must be available.

Determination of dry matter loss by calculated ash content of wood and bark

The experimentally determined ash contents of wood chips with the reference method (sampling bags) are compared with ash contents calculated for crop-dependent mixing ratios of separated wood and bark. In order to ensure an accurate estimation of dry matter losses with the calculated ash contents, the following parameters must be determined first:

- Bark content relative to the respective stem diameter;
- Bark content of branches;
- Proportion of branches of single trees.

The analyses of the above mentioned parameters were carried out for 5 different typical stem diameters at cutting height (SDCH of 3, 6, 11, 15 and 19 cm) of the predominant poplar variety used in the trial (clone Max 4).

For the determination of the bark content relative to SDCH, the stems were debranched and cut into pieces of 50 cm length. For each piece the average stem diameter has been measured; then it was debarked and the proportion of bark resulted from the ratio of dry bark to total dry mass of the single piece. For every SDCH-class (3, 6, 11, 15 and 19 cm) 3 trees

have been analysed accordingly. The results have been separately compiled for every SDCH-class to present the correlation between bark content and stem diameter alongside the stem.

The high number of branches per tree made it quite difficult for all the branches to be debarked for analysis. Therefore, the bark content of branches was determined based on a representative selection of branches following the same procedure as for the stems.

Based on the determined proportion of branches, the bark content of all branches could be estimated. For the determination of the branch proportion, branches of different trees were separated, dried and their mass proportion relative to the dry mass of the entire tree was calculated. The calculation considering all relevant parameters was carried out according to Equation 2.3.

$$bc_{tree} = \frac{\sum_1^n m_b(stem) + \sum_1^n m_b(branch)}{\sum_1^n m_b(stem) + \sum_1^n m_b(branch) + \sum_1^n m_w(stem) + \sum_1^n m_w(branch)} \times 100 \% \quad (2.3)$$

$$\text{with } \sum_1^n m_b(branch) = bc_{branch} \times \sum_1^n m_b(stem) \times x_{branch}$$

bc_{tree}	<i>bark content of whole tree on dry basis</i>	[%]
$bc_{(branch)}$	<i>bark content of branches on dry basis</i>	[%]
$m_b(stem)$	<i>bark mass of stem on dry basis</i>	[kg]
$m_b(branch)$	<i>bark mass of branches on dry basis</i>	[kg]
$m_w(stem)$	<i>wood mass of stem on dry basis</i>	[kg]
$m_w(branch)$	<i>wood mass of branches on dry basis</i>	[kg]
x_{branch}	<i>branch proportion on dry basis</i>	[%]

Based on the specific ash content of wood as well as bark along with the information about the wood-bark-ratio of a tree, the ash content for the entire tree can be calculated with Equation 2.4. At the start of the storage the bark content was measured, which has been considered as a constant for all calculations concerning ash_c .

$$ash_c = \frac{bc_{tree} \times ash_{bark} + (100 - bc_{tree}) \times ash_{wood}}{100} \% \quad (2.4)$$

ash_c	<i>calculated ash content based on bark content (bc_{tree})</i>	[%]
bc_{tree}	<i>bark content of whole tree on dry basis</i>	[%]
ash_{bark}	<i>ash content of bark on dry basis</i>	[%]
ash_{wood}	<i>ash content of wood without bark on dry basis</i>	[%]

The statistical evaluation of the relationship between storage duration and ash content of both chips formats was performed by employing a dual factorial, generalized, linear model (variables: time, chip format). Since the measured values were in percent, a binominal distribution was presumed. Additionally, a logit-link-function ensured that the values predicted by the model ranged between 0 and 1. The difference between both chips formats in terms of their ash contents was tested by a T-test. The correlation between the dry matter losses obtained by the sample bag (reference) method and by calculation with the ash contents was characterised by linear correlation coefficients according to Pearson (SAS version 9.3, SAS Institute Inc., USA).

Results

Weather Conditions

Since the drying process in chip piles is largely dependent on the weather conditions, the long term median value (based on the data of the period from 1985 to 2014) of average daily temperatures (10.7°C) and precipitation sum (492 mm) were calculated using the data provided by the German weather service for Mecklenburg-Lower Pomerania [DWD, 2014]. During the 9 months of storage period, an average daily temperature of 12.4°C and a precipitation sum of 561 mm were recorded (Figure 2.2).

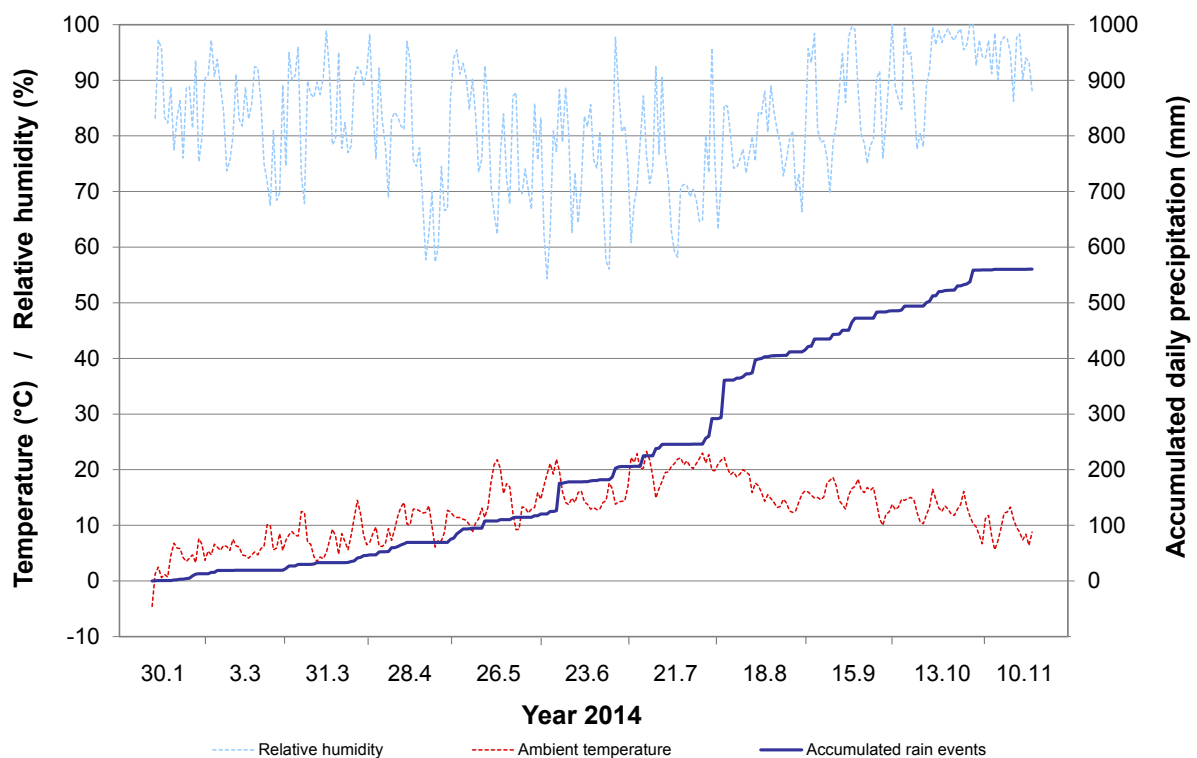


Fig. 2.2: Climate data during storage of chips piles

The comparison between the median value (temperature and precipitation) of long term data and actually observed weather conditions has shown that the trial was carried out under conditions that are typical for North-East-Germany. Although the higher average daily temperature ($\Delta T = 1.7\text{K}$) might have expedited the drying process, it is assumed that the 69 mm higher precipitation sum has countered this effect.

Raw Material Properties

For the calculation of average bark content of whole trees, the average proportion of branches pertinent to the investigated poplar variety was required alongside the

measurement of the bark content of branches and stems. For both coppice plantations, an average branch proportion of 15 %_{db} ($\sigma \pm 2.5$) was determined.

The results in Figure 2.3 show that with increasing SDCH the content of bark declines. For instance, trees with a SDCH of 3 cm have an average bark content of 35.3 %_{db} (Figure 2.3A), while at 19 cm SDCH the bark content amounts to 18.1 %_{db} on average (Figure 2.3E). However, tree sections with the same stem diameters show similar bark contents, regardless of the SDCH. Figure 2.3 represents the relationship between SDCH and average bark contents of the single trees based on the mass weighted median values (Figure 2.3A – E).

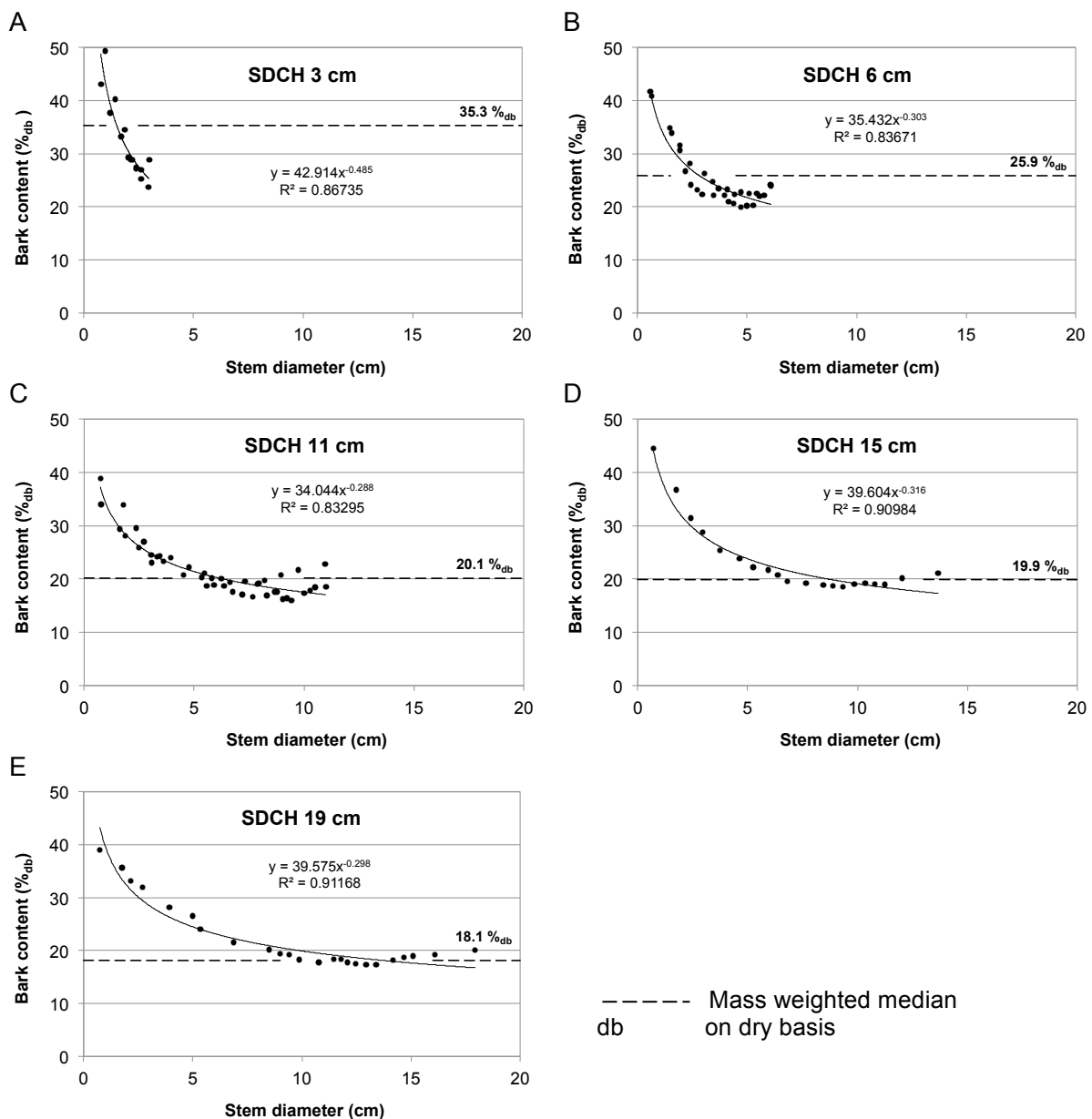


Fig. 2.3: Relation of bark contents of poplar (clone Max) and stem diameter for trees with different stem diameter at cutting height (SDCH)

For the fine wood chips (P31) a bark content of 30.8 %_{db} can be predicted according to Figure 2.4. The coarse wood chips (P45), on the other hand, show a predicted average bark content of 25.5 %_{db}.

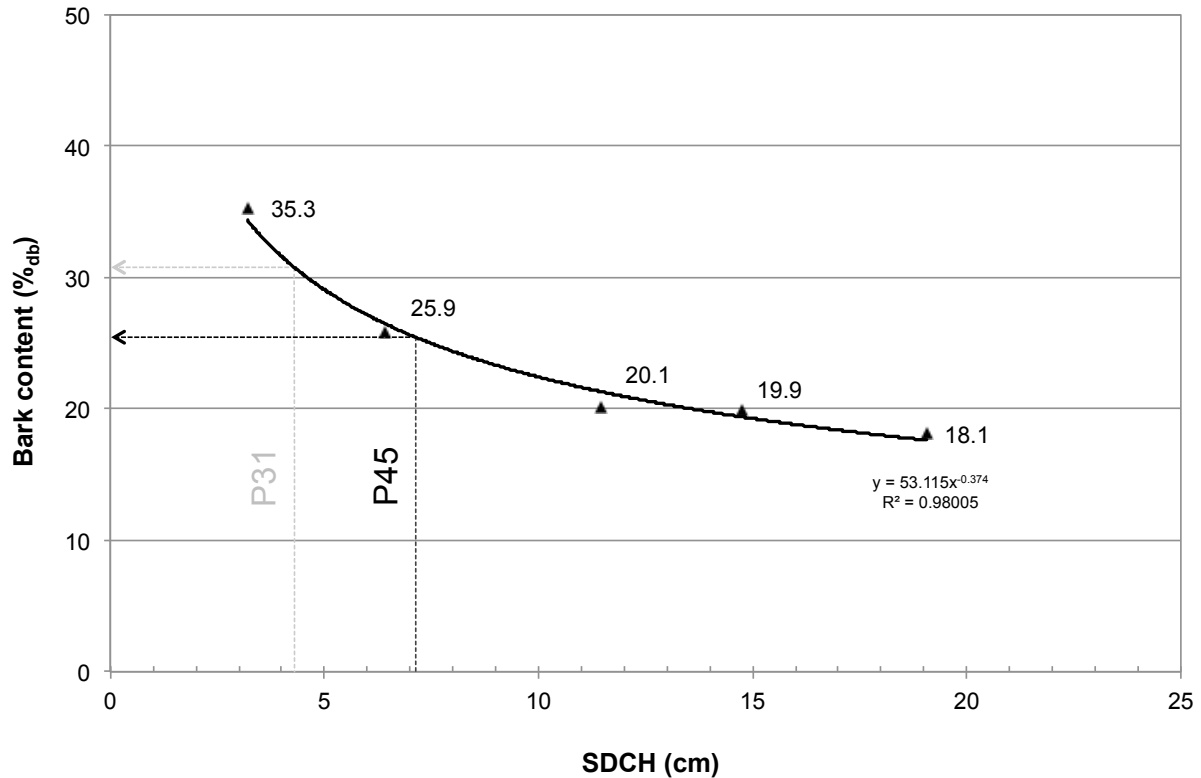


Fig. 2.4: Relation of average bark content of poplar (clone Max) and stem diameter at cutting height (SDCH)

According to the results shown in Table 2.3, coarse wood chips showed 5 percentage points better drying results after 9 months of storage with moisture contents of 29%, as compared to fine wood chips with 34%. The losses in dry mass ($L_{(sb)}$) of both fine and coarse chips formats lie, however, in the same order of magnitude with 22.2% (P31) and 21.4% (P45) respectively.

Tab. 2.3: Moisture content, loss in dry matter (reference method), gross calorific value and ash content of different chips formats at storage intake and storage retrieval

Parameter	Unit	Wood chip format P31		Wood chip format P45	
		storage intake 12-02-2014	storage retrieval 10-11-2014	storage intake 31-01-2014	storage retrieval 10-11-2014
Moisture content	%	59.9 ±0.7	33.8 ±5.3	58.5 ±1.0	28.9 ±6.4
Dry matter loss (reference method)	%	0	22.2 ±2.9	0	21.4 ±3.3
Gross calorific value	MJ kg ⁻¹	17.8 ^b ±0.14	18.1 ^a ±0.10	17.8 ^b ±0.14	18.0 ^a ±0.05
Ash content	%	2.07 ^b ±0.22	2.81 ^a ±0.11	1.49 ^b ±0.21	1.80 ^a ±0.14

± ... σ (standard deviation),

^{a,b} ... Different small letters indicate significantly different groups (Welch-test, $\alpha = 0.05$)

Both for fine and coarse chips the gross calorific value increases slightly yet by statistically significant amount ($p < 0.0001$) from 17.8 MJ kg⁻¹ to 18.1 and 18.0 MJ kg⁻¹ respectively (Table 2.3). As expected, after the analysis according to the different SDCH of both stocks, the ash contents of the stored wood chips differed. The ash content of P31 chips was significantly higher – by 28% ($p < 0.0001$) – than that of P45 chips. Furthermore, there was a considerable difference in the development of the ash contents in the different chip formats over the storage time ($p < 0.0001$). In Figure 2.5 a significant rise can be observed, particularly in the stored bark samples for both chip formats. However, as of 26 May 2014, the ash content of the bark samples virtually levels off. The ash contents of the coarse wood chips samples (P45/chips) and the pure wood samples (P45/wood) remain rather low with only very slightly increasing trend, as compared to the adequate P31-samples. This can be attributed to the higher median SDCH of the harvest stock (Figure 2.4).

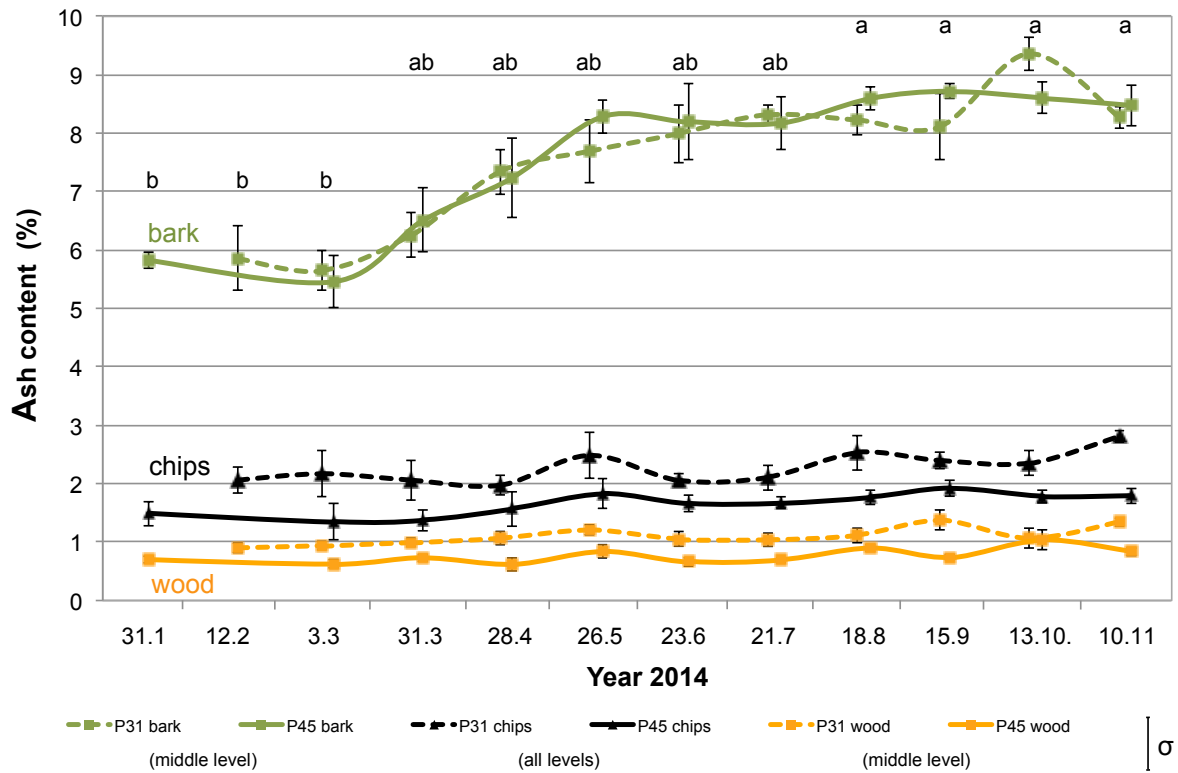


Fig. 2.5: Changes of the average ash contents of fine (P31) and coarse (P45) chips, wood and bark during the storage of 9 months

Based on the respective bark contents determined in Figure 2.4, a theoretically mixed sample (ash_c) was calculated (Equation 2.4). These calculated ash contents (ash_c) along with the resulting dry matter losses (Equation 2.2) are represented for both chip formats in Figure 2.6 in the course of their 9-months storage period.

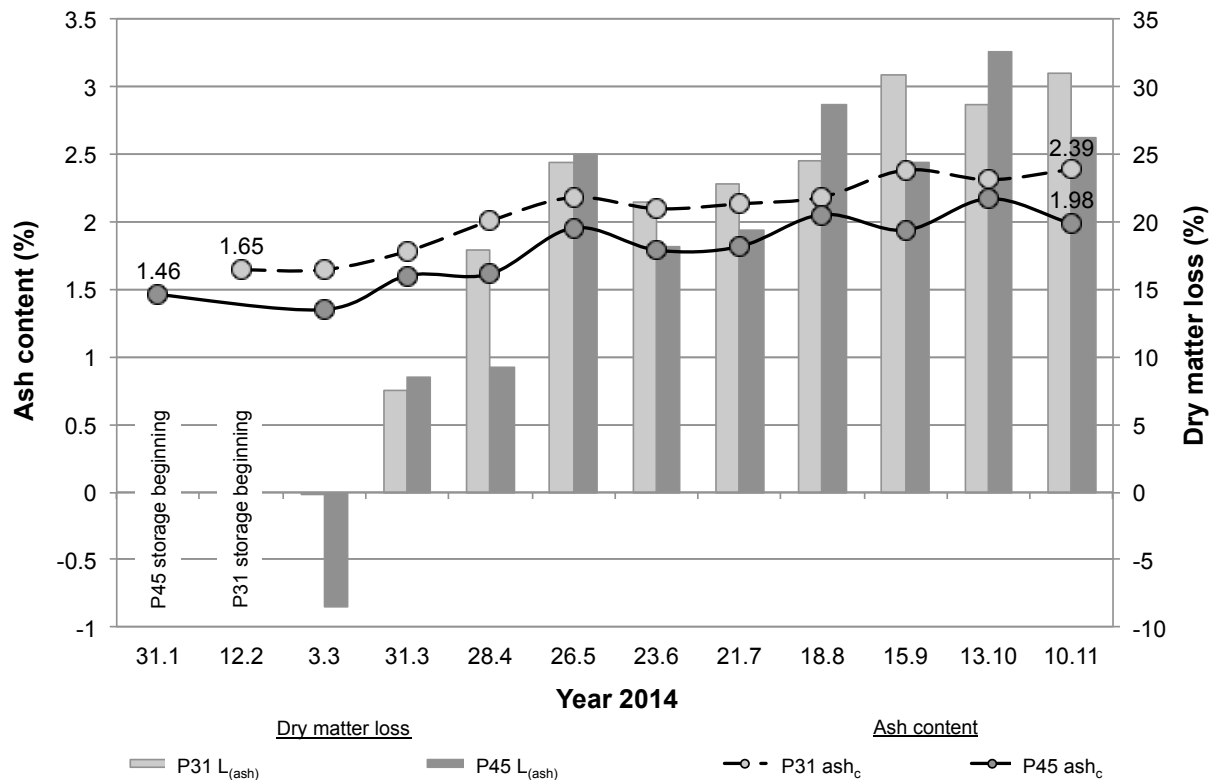


Fig. 2.6: Calculated ash contents and calculated losses in dry matter based on crop-based determined bark contents during 9-months storage of fine (P31) and coarse (45) wood chips

Within the first 4 weeks of storage (until 03 March 2014), dry matter losses cannot be reliably determined due to inhomogeneous drying processes (Figure 2.6). This can result in even negative values calculated for dry matter losses within this period. Findings of previous work by PECENKA ET AL. 2014 confirm these results.

The calculated ash contents and losses in dry mass of both wood chip types continued to soar until 26 May 2014 (Figure 2.6). During the following period, the dry matter losses increase slightly to approx. 20% (P31) and 24% (P45). At storage retrieval (on the 10 November 2014), dry matter losses of 31.0% (P31) and 26.2% (P45) can be estimated based on the calculated ash contents.

Figure 2.7 shows a comparison of both methods for the determination of dry matter losses (reference method vs. dry matter loss calculation based on ash contents).

Evidently, the values of the dry matter loss determined with the reference method using sample bags ($L_{(sb)}$) lie below the theoretically calculated ash based dry matter losses ($L_{(ash\ c)}$) across the entire storage period: by 3.7 percentage points (P31) and 2.2 percentage points (P45) respectively.

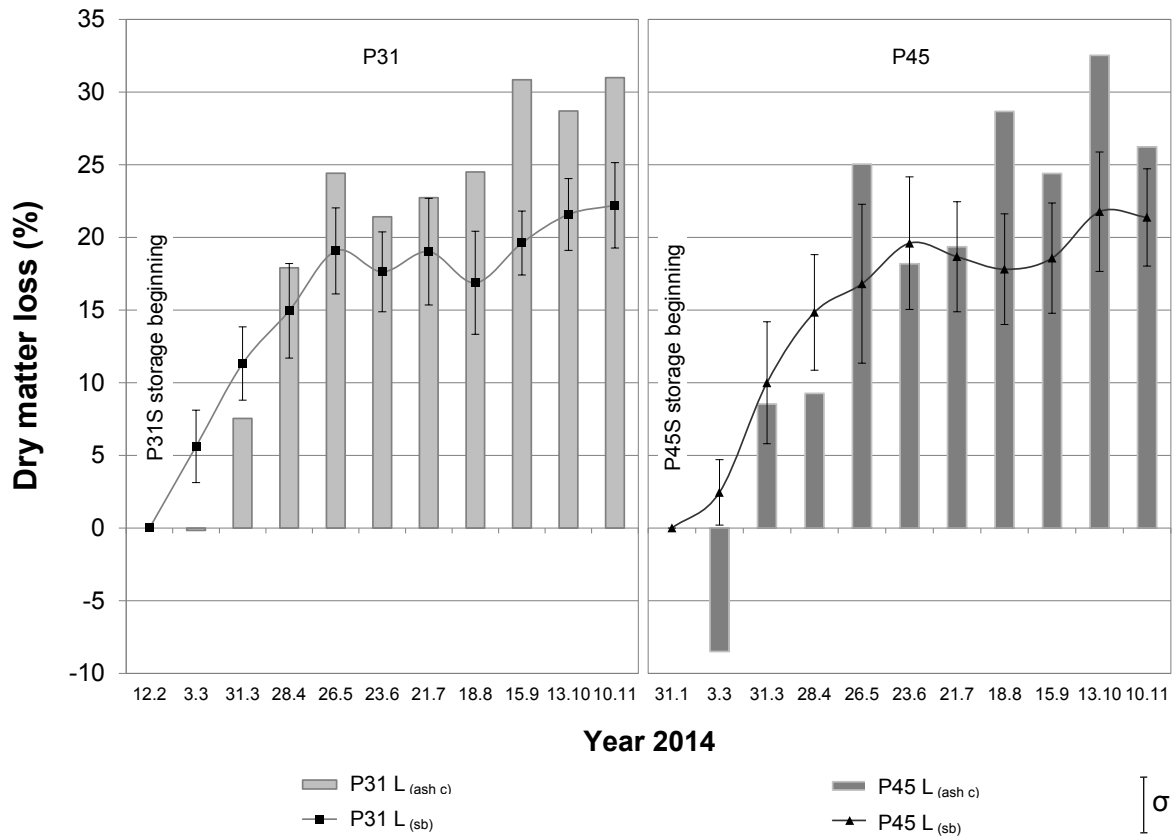


Fig. 2.7: Comparison of differently determined dry matter losses during storage of fine (P31) and coarse (P45) wood chips

A high correlation to the values achieved by a reference method is the prerequisite for reliable applicability of the developed method to calculations of dry matter losses. Basis for the demonstrated relations shown in Figure 2.6 are the calculated ash contents, which were determined based on the wood-bark-ratio of single trees according to Equation 2.4. The changes of ash contents in the bark are seemingly a suitable indicator for the development of dry mass contents due to their marked increase (Figure 2.5) over the storage. Therefore, statistical correlations between the dry matter losses and ash contents of chips, bark, and wood were investigated across the entire duration of storage (Table 2.4).

Tab. 4: Correlation of dry matter losses observed with the reference method (sample bags; $L_{(sb)}$) with the measured (ash_{chips, bark, wood}) and calculated ash contents (ash_c) during the storage of fine (P31) and coarse (P45) chips

Date	P31					P45				
	$L_{(sb)}$	ash _{chips}	ash _{bark}	ash _{wood}	ash _c	$L_{(sb)}$	ash _{chips}	ash _{bark}	ash _{wood}	ash _c
Year 2014										
31.1/12.2	0 ^g	2.07 ± 0.22 ^{de}	5.87 ± 0.56 ^b	0.90 ± 0.08 ^a	1.65	0 ^g	1.49 ± 0.21 ^{cd}	5.83 ± 0.14 ^b	0.69 ± 0.06 ^a	1.46
3.3	5.6 ± 2.5 ^f	2.17 ± 0.39 ^{cde}	5.64 ± 0.34 ^b	0.94 ± 0.07 ^a	1.64	2.4 ± 2.3 ^f	1.34 ± 0.31 ^d	5.46 ± 0.44 ^b	0.62 ± 0.08 ^a	1.35
31.3	11.3 ± 2.5 ^e	2.06 ± 0.35 ^{de}	6.26 ± 0.38 ^{ab}	0.99 ± 0.06 ^a	1.78	10.0 ± 4.2 ^e	1.37 ± 0.18 ^d	6.51 ± 0.54 ^{ab}	0.73 ± 0.06 ^a	1.60
28.4	14.9 ± 3.3 ^d	1.97 ± 0.17 ^e	7.34 ± 0.38 ^{ab}	1.06 ± 0.12 ^a	2.01	14.8 ± 4.0 ^d	1.57 ± 0.29 ^{bcd}	7.24 ± 0.69 ^{ab}	0.62 ± 0.11 ^a	1.61
26.5	19.1 ± 3.0 ^{bc}	2.48 ± 0.39 ^{abc}	7.69 ± 0.54 ^{ab}	1.21 ± 0.09 ^a	2.18	16.8 ± 5.5 ^{cd}	1.82 ± 0.26 ^{ab}	8.28 ± 0.28 ^{ab}	0.84 ± 0.11 ^a	1.95
23.6	17.6 ± 2.7 ^{cd}	2.06 ± 0.10 ^{de}	7.99 ± 0.50 ^{ab}	1.05 ± 0.12 ^a	2.10	19.6 ± 4.6 ^{abc}	1.66 ± 0.14 ^{abcd}	8.19 ± 0.65 ^{ab}	0.66 ± 0.08 ^a	1.79
21.7	19.0 ± 3.7 ^{bc}	2.11 ± 0.22 ^{de}	8.32 ± 0.17 ^{ab}	1.04 ± 0.12 ^a	2.13	18.7 ± 3.8 ^{bc}	1.67 ± 0.10 ^{abcd}	8.17 ± 0.45 ^{ab}	0.69 ± 0.05 ^a	1.81
18.8	16.9 ± 3.5 ^{cd}	2.53 ± 0.29 ^{ab}	8.22 ± 0.25 ^a	1.11 ± 0.12 ^a	2.18	17.8 ± 3.8 ^c	1.76 ± 0.12 ^{abc}	8.59 ± 0.19 ^a	0.90 ± 0.05 ^a	2.05
15.9	19.6 ± 2.2 ^{abc}	2.40 ± 0.15 ^{bcd}	8.11 ± 0.57 ^a	1.37 ± 0.17 ^a	2.38	18.6 ± 3.8 ^c	1.93 ± 0.14 ^a	8.72 ± 0.12 ^a	0.74 ± 0.05 ^a	1.94
13.10	21.6 ± 2.5 ^{ab}	2.35 ± 0.21 ^{bcd}	9.37 ± 0.29 ^a	1.06 ± 0.17 ^a	2.31	21.8 ± 4.1 ^a	1.79 ± 0.11 ^{ab}	8.60 ± 0.26 ^a	1.03 ± 0.17 ^a	2.17
10.11	22.2 ± 2.9 ^a	2.81 ± 0.1 ^a	8.28 ± 0.19 ^a	1.35 ± 0.17 ^a	2.39	21.4 ± 3.3 ^{ab}	1.80 ± 0.14 ^{ab}	8.47 ± 0.35 ^a	0.84 ± 0.07 ^a	1.98
correlation coefficient (r)		0.55	0.91*	0.74*	0.94*		0.80*	0.96*	0.53	0.89*

± ... = σ (standard deviation), * Significantly different from 0, ^{a,b,c,d,e,f,g} = Different letters indicate significant difference between dates (multiple pairwise comparison; adjustment for multiple comparison simulated), all tests at significance level $\alpha = 0.05$

The statistical analysis indicates clearly that particularly the measured ash content of the bark samples ($r = 0.91$ P31 / $r = 0.96$ P45) and the calculated ash contents from wood and bark ($r = 0.94$ P31 / $r = 0.89$ P45) show high correlation coefficient in comparison with the correlation of dry matter losses. Table 2.4 also shows that the ash contents of both chips formats (P31, P45) already differed significantly at storage intake ($p < 0.0001$).

Different plant densities and rotation times lead to different SDCH. In consequence, higher SDCH feature lower bark contents, which results in lower ash contents. Figure 2.8 shows this relationship based on the different bark contents for both wood chip formats. If the ash content is already high at the time of storage intake, it may lead to ash contents exceeding the approved maximum limit of 3% (EN ISO 17225-4) at storage retrieval. Although the measured ash contents of wood chips are subjected to a higher measurement inaccuracy ($n=9$, Figure 2.5), the same relationship can be found here.

The average SDCH of trees used for the production of fine wood chips (P31) was 4.3 cm, corresponding to a bark content of 30.8% (Figure 2.4). In this case, just 3 months of storage would cause the material to exceed the approved ash limits (Figure 2.8A); at storage retrieval after 9 months the limit would be exceeded even by almost 0.5 percentage points. The coarse wood chips (P45), however (7.1 cm SDCH and corresponding to a bark content of 25.5%), remain within the limits set by standards across the entire course of storage (Figure 2.8B).

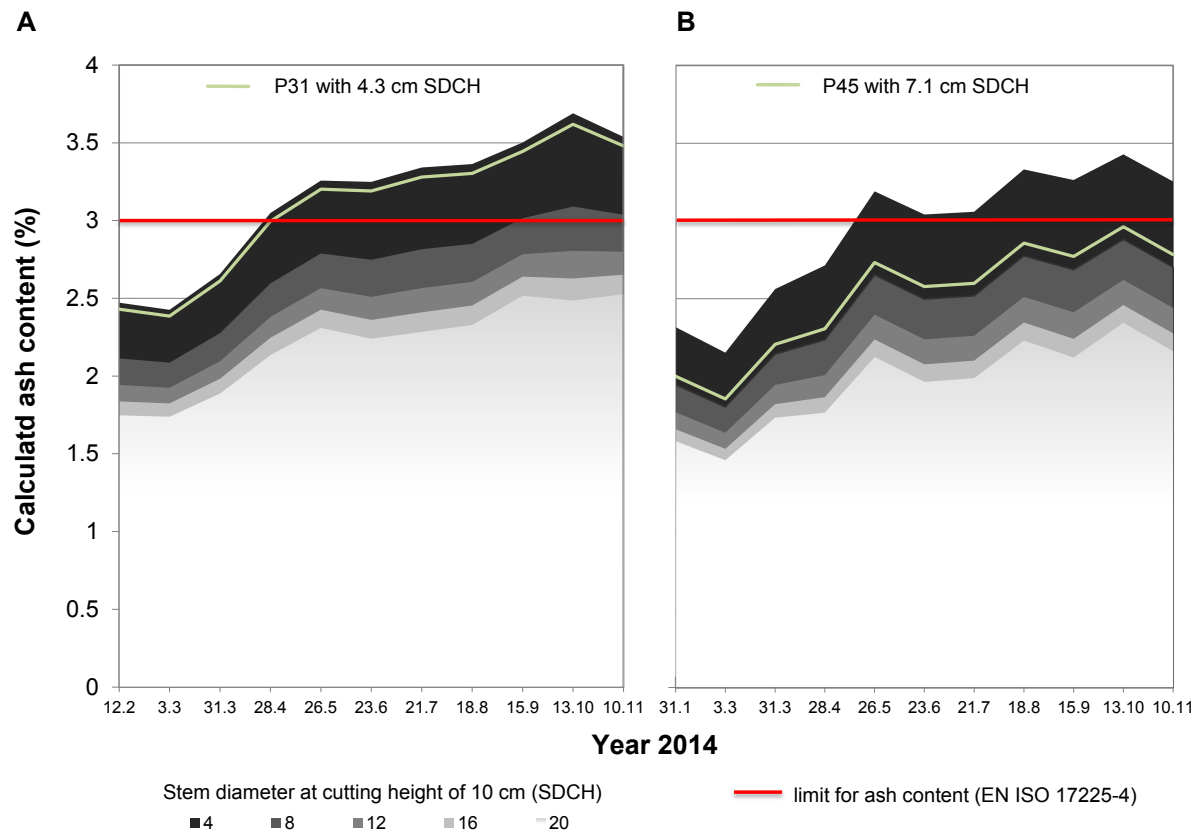


Fig. 2.8: Calculated ash contents relative to different bark contents across 9-months storage of fine (P31) and coarse (P45) wood chips

Discussion

A reliable, representative and accurate determination of dry matter losses by means of the sample bag method over the entire long storage periods is extremely time- and labour-intensive. Alternatively, the reduction of biomass could be determined by the change in ash contents during storage. This procedure is indisputably simpler, since only samples for the determination of ash contents are necessary. The presented research work demonstrated that the ash contents in wood chips are distributed quite heterogeneously. The main reason behind this is the strong variation of bark content in the samples. By increasing the number of samples/sampling bags, statistically reliable values could be generated. This, however, would cause a considerable increase in labour.

By calculations of theoretically mixed samples consisting of separated wood and bark, the extent of sampling can be reduced and hence the difficulty regarding the aforementioned variations of ash contents could be successfully surmounted. This, however, needs exact information about the wood-bark-ratio of the trees to be harvested.

The bark content is not only governed by the conditions at location and the respective genotype of the tree, but also substantially dependent on the SDCH [AMTHAUER & SEYMOUR, 2011]. Literature reports bark contents for poplar ranging from 10 to almost 30%. The inversely proportional relationship between SDCH and bark contents, however, is rarely demonstrated [BOJANA ET AL., 2002]. In order to procure exact information about this correlation, which is crucial for a correct determination of the ash content, bark contents for different SDCH (3 to 19 cm) had to be identified. Based on this, the theoretical ash content of the respective batch could be determined with only a few samples, as demonstrated in this work on the example of poplar, clone Max.

Figure 2.7 shows a comparison of the two different dry matter losses identified by both methods (sample bag, calculated ash contents). Across the entire course of storage, the reference values originating from the sample bags are lower by 3.7 percentage points (P31) and 2.2 percentage points (P45) respectively. The marked increase of dry matter loss ended after approximately 4 months of storage (by 26 May 2014). Comparing the median values of dry matter losses stemming from both methods as of the 4th month of storage, the experimental values ($L_{(sb)}$) lag the theoretically calculated values even by 6.7 percentage points (P31) and 5.8 percentage points (P45) respectively.

One of the reasons behind these method-related differences in dry matter losses could be the high sensitivity of the sample bag method to moisture contents. For example, if the moisture content in the calculation rises by 1%, the resulting dry matter losses increase up to 2 percentage points. Furthermore, the samples for the calculation of the ash contents were taken only from the middle level, while the sample bags for dry matter loss determination

were taken from all 3 levels. This might have caused even further deviation between the two methods.

Besides the calculated ash contents (ash_c), the ash contents of the separated bark samples (ash_{bark}) showed the highest correlation to dry matter loss. Presumably, changes of ash contents of separated bark samples would also suffice to achieve reliable predictions of the dry matter losses. Preparing the bark samples from the fine fraction of the particle size analysis (screen size < 1 mm) would further simplify the method, because the bark sampling for ash content determination at storage intake would no longer be necessary. This, however, requires the development of a model based on thorough investigations conducted on other tree species, cultivars, and clones at various locations.

From a practical point of view, longer rotation times are recommended. According to Figure 2.8, average SDCH of 10 cm at harvest is desirable to ensure bark contents below 20% and hence post storage ash contents below 3%. At SDCH lower than 10 cm, the diameter has particularly strong impact on both the bark content and the ash content. The bark content falls by 3.1 percentage points per cm at SDCH below 10 cm, whereas the reduction of bark content above 10 cm SDCH is only marginal, at about 0.5 percentage points per cm.

Overall, it must be considered that the ash content during storage always increases due to the decomposition of the organic proportion. High ash contents already at storage intake are very much likely to end up with exceeding the limit of maximum ash contents of 3% according to EN ISO 17225-4 after storage.

The beneficial longer harvesting intervals push the well tried and tested agricultural harvesting technology such as the classical forage harvesters to their technical limit owing to the occurring higher SDCH. Most forage harvesters can utilize their full technical potential at SDCH around 8 – 10 cm. In plantations with average SDCH of 10 cm, however, maximum diameters of 15 cm occur quite frequently. Trees with larger diameters can be harvested with tractor-mounted chippers. The ATB mower-chipper technology used in this trial is currently suitable for SDCH up to 20 cm. SDCH beyond 20 cm is exclusively manageable with forestry machineries, which are considerably expensive [SCHWEIER, 2013]. These additional costs of agroforestry harvest must be compared with the added value by quality improvement from an economic perspective.

Conclusions

As shown on the example of poplar, clone Max, the loss of dry mass in wood chips storage can be estimated reliably with acceptable accuracy from ash content, while the calculations based on theoretical mixes of wood and bark offer substantial advantages.

Especially the measured ash content of separated bark showed very high correlations to the dry matter losses determined with the reference method. Therefore, these bark samples appear to be particularly suitable for the calculation of dry matter losses. Sole precondition for such a simplified method is for the bark samples to be available at each measurement run. Reliable information about the tree specific bark content with respect to the SDCH is required as well. The development of a method for easier determination of dry matter losses based on this research would be considerably useful, especially in deriving the course of storage loss progression exclusively from a few bark samples.

Generally, it can be postulated that the quality of wood chips from poplar as fuel is principally governed by the SDCH of the trees at harvest, while the chips format exhibits a less pronounced impact. Therefore, longer rotation cycles leading to higher stem diameters at harvest and lower ash content in wood chips from SRC are recommended. However, efficient harvest equipment must be available for economic harvest of poplar plantations with SDCH of 15 cm or higher.

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Chapter three

Continuous weighing of a pile of poplar wood chips – A comparison of methods to determine the dry matter losses during storage

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Abstract

The measurement of dry matter losses occurring during the storage of wood chips is of crucial importance for understanding the efficiency of bioenergy supply chains.

When obtaining representative measurements of a whole storage heap, it is necessary to distribute a large number of samples over cross sections of the pile. The recovery of these samples can be very labour-intensive, and can lead to major disturbances in the pile. Accordingly, this method is not suitable for periodic examinations of storage heaps.

In this study, two 100 m³ piles (P1 and P2) of fine wood chips from poplar were investigated over a period of 228 days of storage. The P1 pile was used to compare the different methods in which to determine the moisture content changes and dry matter losses during storage. The results generated by the balance bag method (M1) were compared with three alternative methods. These alternative methods (M2 – M4) involved the analysis of moisture content and mass changes in balance bags within measuring columns located within the heap (M2), moisture content and mass changes occurring in the entire pile (M3), and from changes in ash contents of samples in balance bags within the measuring columns (M4).

dry matter losses of 23.3% and 22.7% were determined using methods M1 and M2, respectively. The dry matter losses calculated using M3 and M4 were considerably lower at 13.9% and 16.6%, respectively. The M2 method proved to be the most suitable for periodic determination of storage losses in a similar experimental design.

Keywords

Short rotation coppice, poplar, wood chip, storage, methodology, dry matter loss

Highlights

1. Storage losses of poplar wood chips were investigated with 4 different methods.
2. Representative moisture contents take top priority when determining dry matter losses.
3. Measuring columns are suitable as aids for simple periodic sampling.
4. A large number of samples is necessary to determine ash contents.
5. Determining dry matter losses by weighing a whole pile provides only indicative results.

Introduction

Poplar and willow, grown as short rotation coppice (SRC), have been identified as important bioenergy crops in Europe. As they are fast-growing crops that tend to perform well at poorer quality sites, they offer a potential biomass resource that does not compete for fertile arable land. Such crops also offer a mechanism for decentralising energy supplies and promoting the local use of bioenergy [BOLL ET AL., 2015]. There are also observed benefits to local biodiversity with the uptake of SRC [HAUGHTON ET AL., 2015] meaning they can play an important role in the sustainable intensification of agriculture. Even with these benefits, however, the SRC cropping areas in the EU have stagnated. Despite the introduction of policies that provide financial incentives to farmers, uptake has been limited, with 7,000 ha established in Germany, [PECENKA ET AL., 2014; FNR, 2016], 1,000 ha in Austria [TRETTER & LANG, 2010] and 5,500 ha in the United Kingdom [DON ET AL., 2012]. One of the reasons for this unsatisfactory uptake is the insufficient integration of the ecological benefits of SRC in agricultural support policies (EU Regulation 639/2014) and a prevailing lack of acceptance among farmers [SHERRINGTON & MORAN, 2010].

Uncertainties regarding the technical methods of harvesting and machinery availability have raised additional barriers to farmer confidence in SRC [BOLL ET AL., 2015]. Although harvesting machinery manufacturers have successfully tackled many of the problems encountered through technological developments and innovations, [EHLERT ET AL., 2013; PECENKA ET AL., 2015; MANZONE & BALSARI, 2015; BECENETTI ET AL., 2016], there still remains a clear demand for research into efficient post-harvesting storage [PETTERSSON ET AL., 2007; HE ET AL., 2012; HORVATH ET AL., 2012; PARI ET AL., 2013; SUCHOMEL ET AL., 2014; MANZONE 2015; ALAKOSKI ET AL., 2016; KÜHMAIER ET AL., 2016]. Current research focuses on developing low-cost methods of storage that reduce the dry matter losses and preserve the quality of the biomass fuel [HEINEK ET AL., 2013; MANZONE ET AL., 2013; BARATONI ET AL., 2014; PECENKA ET AL., 2014; LENZ ET AL., 2015; PARI ET AL., 2015; WHITTAKER ET AL., 2016].

When harvested in winter or early spring, wood chips from SRC have a moisture content of between 50 – 60% (defined as water mass fraction or moisture content on the wet basis). The biomass must then be stored until the following winter when it is required for heating. In bioelectricity supply chains it is also beneficial to simultaneously store and dry the material until required, and in all supply chains, a storage phase provides a means to buffer between periods of supply and demand [JIRJIS, 1995]. Currently adopted storage methods either involve higher technical efforts and costs (e.g. technical ventilation, whole tree storage) or lead to high dry matter losses (e.g. uncovered storage with natural drying). Due to cost limitations, it is common practice to allow wood chips to dry naturally in piles stored in the

open. This leads to dry matter losses of between 6.6 and 26.6%, as reported in relevant literature (Table 3.1).

Tab. 3.1: Magnitude of dry matter losses during storage of short rotation coppice and forestry-derived wood chips reported in relevant literature

Wood type (particle size category)	Dry matter loss		Pile volume		Storage duration		Dry matter loss % / storage duration	Land/Region	Moisture content		Sample weight kg _{wb}	Loss determining method	Reference
	% / month	m ³	days	Period	X _{in}	X _{out}							
Poplar crowns (P31)	1.4	117	189	Mar. – Sep.	6.6	Central Italy (Monterotondo)	54	31	ND	Sample bags	BARONTINI ET AL. 2014		
Poplar (P63)	1.6	20	170	Mar. – Sep.	9.3	North-West Italy	39	25 – 35	6,000**	Whole pile	MANZONE ET AL. 2013		
Poplar crowns (P31)	1.6	117	189	Mar. – Sep.	10.0	Central Italy (Monterotondo)	54	31	35,000**	Whole pile	BARONTINI ET AL. 2014		
Poplar (fine*)	1.8	ND	120	Mar. – Jun.	7.2	North Italy	62	26	ND	Sample bags	PARI ET AL. 2015		
Poplar (P31)	2.3	1,000	271	Feb. – Nov.	22	North-East Germany	60	34	2	Sample bags	LENZ ET AL. 2015		
Poplar (P45)	2.3	600	284	Jan. – Nov.	21	North-East Germany	59	29	2	Sample bags	LENZ ET AL. 2015		
Poplar (fine*)	3.2	ND	120	Mar. – Jun.	12.9	North-Italy	62	34	ND	Sample bags	PARI ET AL. 2015		
Poplar (P31)	3.2	500	223	Jan. – Aug.	24	North-East Germany	62	33	2	Sample bags	PEGENKA ET AL. 2014		
Poplar trunk (P31)	3.4	117	189	Mar. – Sep.	21.6	Central Italy (Monterotondo)	48	34	ND	Sample bags	BARONTINI ET AL. 2014		
Poplar (P45)	3.6	500	223	Jan. – Aug.	27	North-East Germany	60	34	2	Sample bags	PEGENKA ET AL. 2014		
Poplar trunk (P31)	4.2	117	189	Mar. – Sep.	26.6	Central Italy (Monterotondo)	48	34	35,000**	Whole pile	BARONTINI ET AL. 2014		
Willow (fine*)	2.6	540	210	Mar. – Oct.	18	England (East Midlands)	54	39	3 – 4	Sample bags	WHITTAKER ET AL. 2016		
Willow (fine*)	6.5	320	97	Apr. – Jul.	21	England (South-East)	50	43	84,000	Whole Pile	WHITTAKER ET AL. 2016		
Spruce (fine*)	1.0	960	232	Apr. – Dec.	8.0	Italy (South Tyrol)	42	43	1.5 – 2	Sample bags	HEINEK ET AL. 2013		
Spruce (fine*)	1.6	700	258	Apr. – Jan.	13.6	Italy (South Tyrol)	55	43	1.5 – 2	Sample bags	HEINEK ET AL. 2013		

FM ... fresh matter, * according to Standard EN ISO 17225-1 no allocation to a particle size category is possible, ** Assumed mean bulk density 334 kg m⁻³

ND ... no data, X_{in} ... moisture content of the wood chips on storage intake, and X_{out} ... on storage uptake

Not only does the tree species, particle size, weather conditions, and experimental set-up influence the dry matter losses during storage, but the method used to determine the dry matter losses is also important. It is essential to use reliable and accurate methods wherever possible in order to reduce errors and/or uncertainties when comparing losses between different storage conditions. Additionally, the adopted method must be feasible with respect to labour input and costs. In the literature studied, the most widespread method is to use balance bags, where the mass of a filled sample bag (generally made of netting material) is determined at the beginning and end of the storage experiment. The differences in dry matter content in the bags then determine the losses incurred between the two sampling times. Various studies adopting this method find different results (see Table 3.1). For example, monthly dry matter losses during the storage of poplar chips are reported to range from 1.4 to 4.2% ($\bar{\sigma} = 2.6\%$). In willow chips, mean monthly dry matter losses of 4.6% have been reported. In comparison with SRC, the dry matter losses during storage of forest residue chips are 1.3% per month [HEINEK ET AL., 2013]. The different tree species could explain these differences, however the different weather conditions could also play a role: in Southern Europe wood chip storage gave monthly dry matter losses of 2.2% [MANZONE ET AL., 2013; BARONTINI ET AL., 2014; PARI ET AL., 2015], and in Northern Europe they were 3.4% [PECENKA ET AL., 2014; LENZ ET AL., 2015; WHITTAKER ET AL., 2016]. The indication of dry matter losses per month over longer storage periods is only a rough simplification. Typically, the increase of dry matter losses over storage time is non-linear [LENZ ET AL., 2015]. Also, the balance bag method can be employed in different ways, and the use of different bag materials, mesh widths, 'trickling' losses from the bags, sample sizes, the number of samples, sampling areas and the disturbances of the pile structure during sampling events can all influence the final results [HORVATH ET AL., 2012; MANZONE ET AL., 2013; BARONTINI ET AL., 2014; LENZ ET AL., 2015; WHITTAKER ET AL., 2016]. There is also the risk that the bags can be damaged during storage, or as they are withdrawn at the end of the experiment. Therefore, the uncertainties in this method warrant the exploration of alternative methods.

The dry matter content is determined by the mass and moisture content of a sample, hence measuring the latter effectively is vital to determine changes in dry matter. The rate of drying within a wood chip pile can vary widely, and can depend on physical aspects such as the particle size, type of wood, pile volume, and prevailing winds and solar exposure. Major deviations in the moisture content can arise, therefore the accuracy of the determined moisture content will depend on the positioning and number of samples measured. Due to heat convection and airflow within wood chip piles, there can be areas of condensation and re-distribution of moisture, particularly in the pile crest or 'chimney' and around the outer layers. In addition, piles located outside are consistently exposed to incoming rainfall, and

the two effects lead to the creation of an outer wetter 'crust' [PARI ET AL., 2008; LENZ ET AL., 2015]. Due to the generation of heat in the core parts of the pile, this region can be relatively homogeneous and drier, and this generally represents the bulk of the sampling area. Despite this, previous research has shown that the mixing of the outer layer with the remainder of the heap effectively re-wets the material [WHITTAKER ET AL., 2016]. For this reason, a detailed analysis on the distribution of moisture content and changes in drying throughout the interior and across the outer layers would help to refine methods for dry matter loss determination.

This study details a number of simultaneous trials to examine alternative approaches to determine dry matter losses during wood chip storage. The aim of the study is to compare three alternative methods with those determined using the conventional balance bag method, as this method can be highly labour intensive and subject to uncertainty, as detailed above. The results of this study will be used to provide recommendations for which methods to employ when determining dry matter losses during wood chip storage.

Material and Methods

Material

A wood chip storage trial was set up on 20 February 2014 at the Leibniz Institute for Agricultural Engineering and Bioeconomy in North Germany (52°26'N; 13°00'E). Two piles were built using 200 m³ (100 m³ for each pile) of freshly harvested fine wood chips from a four-year old SRC crop (poplar, clone Max, first rotation). The double-row plantation (plant spacing: 2.2 m x 0.5 m x 0.6 m) was harvested with a modified forage harvester with an SRC header (New Holland forage harvester FR 9060 with FB 130).

Trial set-up

The harvested material was divided at the storage location and piled onto two platforms of the same design (P1/P2). Each of these platforms had a base area of 54 m² (6 m x 9 m). Both piles were covered by a semi-permeable nonwoven fleece (Toptex, 2.5–3 mm, Tencate, Austria) in order to minimise the infiltration of rainwater. The breathable fleece allows emerging water vapour to escape (Figure 3.1A/3.1B).

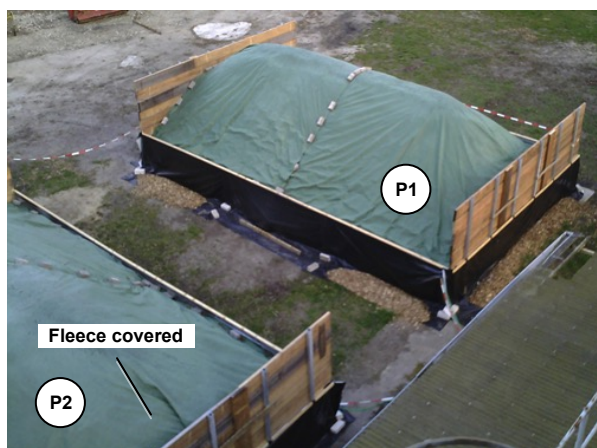


Fig. 3.1A: Covered wood chip piles on platforms P1 and P2

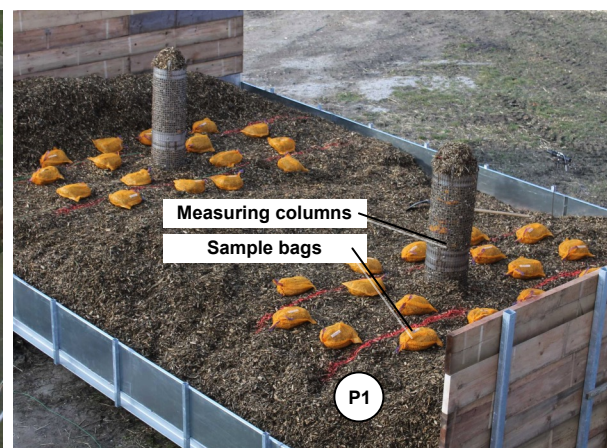


Fig. 3.1B: Distribution of sample bags and measuring columns on platform P1

The two piles were sampled in different methods according to different experimental set-ups and research goals. The material on platform P1 formed the basis for a regular examination of periodical changes in moisture content and dry matter as well as the distribution of the moisture content in the interior of the pile. By contrast, on platform P2 only changes in the moisture content of material in the upper layer of the pile (0 – 0.6 m) were analysed.

Experimental set-up

The current study examines the following experimental methods followed in order to determine dry matter losses during wood chip storage:

M1: Determining mass changes and moisture content of samples from balance bags, distributed across a section of the storage pile (reference method);

M2: Determining mass changes and moisture content of samples from balance bags arranged in measuring columns in the pile core;

M3: Determining mass changes through periodic weighing of the entire pile and moisture content of samples from pile cross sections;

M4: Determining ash contents from samples in balance bags, arranged in measuring columns in the pile core.

All investigations of dry matter losses (M1 – M4) were performed only on platform P1. The pile on platform P2 was used only to evaluate changes of the moisture content in the upper layer of the pile.

Structure of the platforms and periodic measurement regime

When building the P1 pile, 36 balance bags with approximately 2 kg fresh matter of wood chips were prepared. They were distributed at three levels in each half of the pile along with 12 temperature sensors (Figure 3.2). In addition, stainless steel lattice columns filled with wood chips (1.7 m high; 0.4 m diameter; 0.02 m perforation width) [LENZ ET AL., 2015] were installed, containing ten further balance bags (Figure 3.2). Periodic measurements were taken of the net wet mass of the entire pile on P1 over the total period of 228 days. This was performed at 11:00 am every ten days by six load cells located underneath the platform. The storage pile on platform 2 did not contain any measuring apparatus.

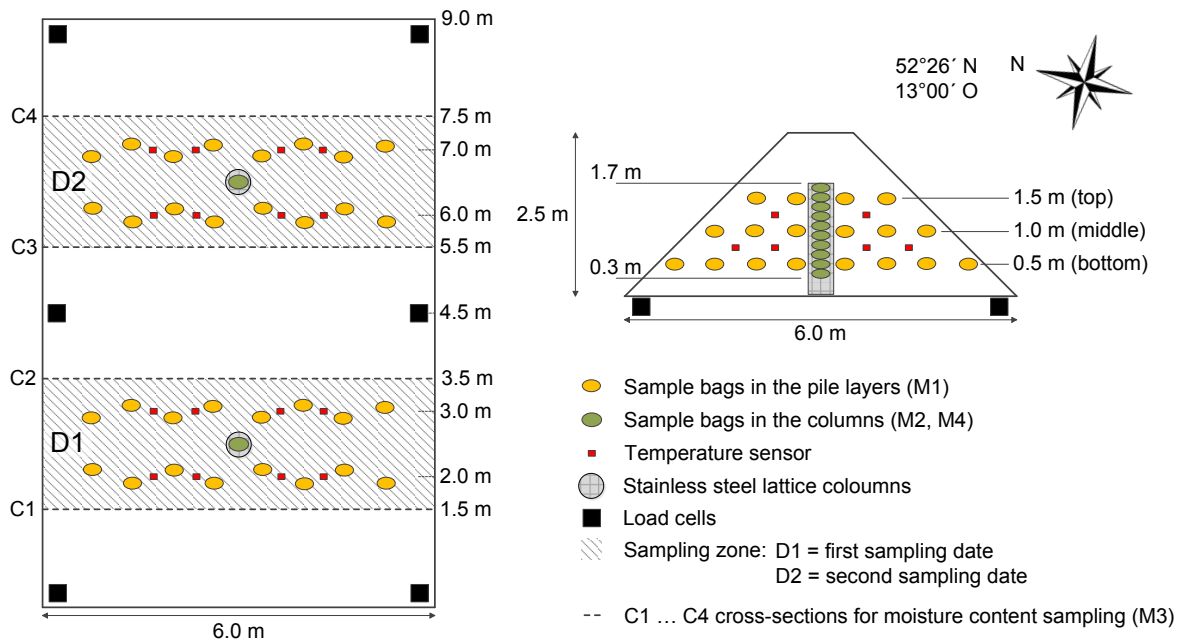


Fig. 3.2: Trial arrangement on platform P1

Sampling

The P1 pile was sampled on day 102 (D1, Figure 3.2) and day 228 (D2, Figure 3.2) after initial set up. This was performed using an excavator to dig a 2 m wide canal (sampling zone) in the pile in order to recover the balance bags, the measuring columns and the temperature sensors. On the first sampling date (day 102) the excavation created two cross-sections in the pile (C1 and C2, Figure 3.2), from which additional samples were obtained to determine the moisture content across the pile. Likewise, on the second sampling date (day 228), the excavation created cross-sections C3 and C4 (Figure 3.2). Figure 3.3 shows the distribution of the sampling points across the cross-sections.

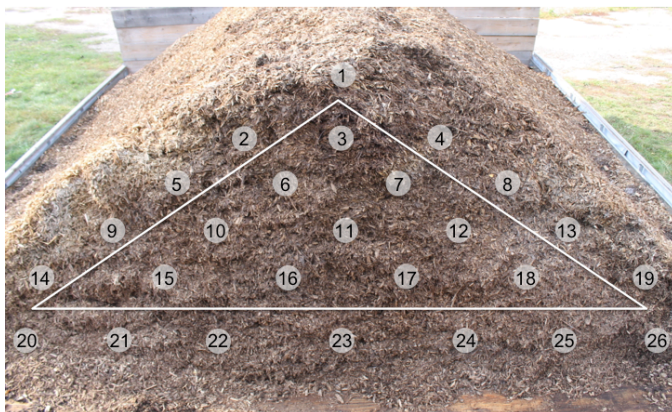


Fig. 3.3: Distribution of the samples over the cross-section of platform P1

After sampling, the canals were backfilled with the wood chips that were previously excavated.

On the P2 pile, on every tenth day throughout the storage period, six samples were taken from seven points in the cross section of the upper layer of the pile (Figure 3.4, A – G). These were used to determine the moisture content from the top down to a depth of 0.6 m. This was performed using a sampler equipped with a measuring rod. The sampling zone shifted 0.3 m along the pile axis on each new sampling event (Figure 3.4).

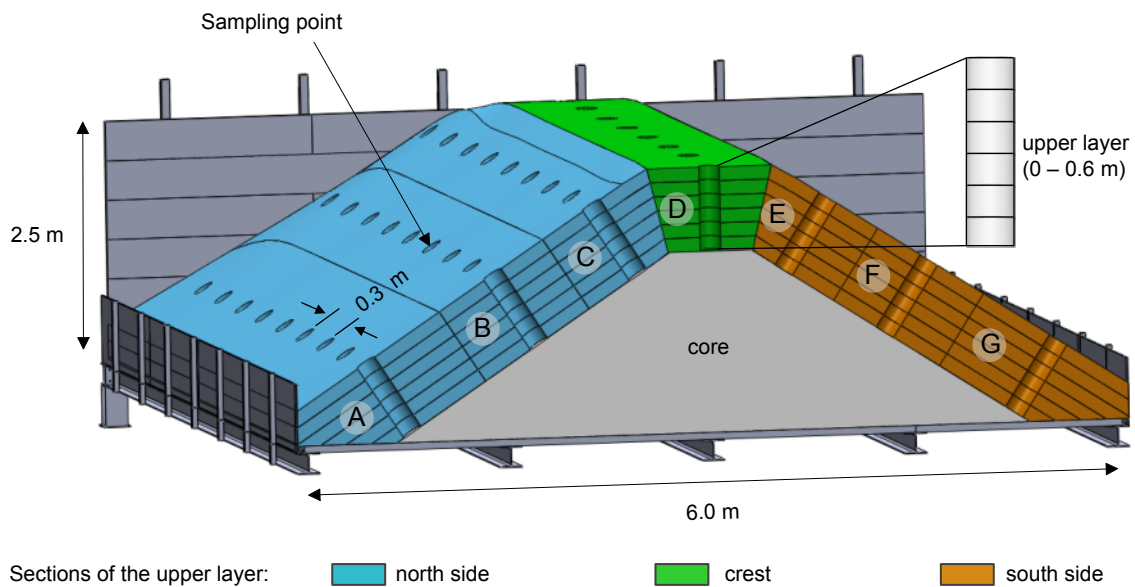


Fig. 3.4: Cross-section of the experimental set-up and distribution of the sampling points on platform P2

Analyses

All samples were analysed for the characteristics listed in Table 3.2.

Table 3.2: Parameters and methods

Parameter	Unit	Number of samples		Methodology
		Storage intake	per sampling	
Particle size distribution	%	n = 7	-	EN ISO 17827-1, EN ISO 17225-1
Gross calorific value	MJ kg ⁻¹	n = 12		EN 14918
Samples from the cross-section			n = 10	EN 14918
Pile mass, platform P1 every 10 days (23 mass)	t	n = 1	n = 1	Bosche load cell Type V50S (weighing range up to 10 t / ± 30kg)
Weather conditions				Weather station at the experiment location
Outdoor temperature	°C			
Precipitation	mm	-	-	
Relative atmospheric humidity	%			
Pile temperatures at height	°C			Almemo Data logger with hot wire, Type K (-200 to +205°C / ±0,1)
0.75 m		n = 16	n = 8	
1.25 m		n = 8	n = 4	
Moisture contents, samples from platform P1	%	n = 84		EN 14774-1
M1 Sample bags in the pile			n = 36	EN 14774-1
M2 Sample bags in the columns			n = 10	EN 14774-1
M3 Samples from the cross-section			n = 52	EN 14774-1
Moisture contents, samples from platform P2				
Samples from the upper layer			n = 42	EN 14774-1
Ash contents, samples from platform P1	%	n = 10		EN 14775
M4 Sample bags in the columns			n = 10	EN 14775
Dry matter losses				
calculated taking changes in moisture contents into account				
M1 Sample bags from the pile	%	-	n = 36	Equation 3.1
M2 Sample bags in the columns	%	-	n = 10	Equation 3.1
M3 Samples from the cross-sections and load cell measurement	%	-	n = 52	Equation 3.1
calculated taking the ash contents into account				
M4 Sample bags in the columns	%	-	n = 10	Equation 3.2

The dry matter losses were calculated using Equation 3.1. In general, the moisture content is defined as the proportion of mass of water in the wet material (on wet basis). All other values, such as dry matter losses or ash contents are defined as mass fractions of the dry basis.

$$L = \left(1 - \frac{m_{out}(100 - x_{out})}{m_{in}(100 - x_{in})}\right) \times 100 \% \quad (3.1)$$

L	<i>dry matter losses</i>	[%]
m_{in}	<i>mass of material taken into storage on wet basis</i>	[kg]
m_{out}	<i>mass of material retrieved from storage on wet basis</i>	[kg]
x_{in}	<i>moisture content of the material taken into storage</i>	[%]
x_{out}	<i>moisture content of the material retrieved from storage</i>	[%]
wb	<i>on wet basis</i>	

The dry matter losses, estimated by using the change in ash contents at different times during storage (time i), were calculated using Equation 3.2.

$$L_{(ash)i} = 1 - \left(\frac{ash_{in}}{ash_i}\right) \times 100\% \quad (3.2)$$

$L_{(ash)i}$	<i>dry matter losses via ash content at time, i</i>	[%]
ash_{in}	<i>ash content at storage start</i>	[%]
ash_i	<i>ash content at time, i</i>	[%]

In order to use the results of the periodic weighing operations to determine gradual dry matter losses, it would have been necessary to examine representative moisture content samples at the same time. This could not be performed, however, to limit disruption of the main pile. A continuous profile of moisture content changes was therefore interpolated via polynomial regression from the moisture content taken from the fresh samples and from those taken from the cross section on both sampling dates (Equation 3.3).

$$x_i = a \text{ day}_i^2 - b \text{ day}_i + c \quad (3.3)$$

x_i	<i>moisture content at time, i</i>	[%]
day_i	<i>storage day, i</i>	[d]
a, b, c	<i>constants</i>	

Statistics

A bifactorial variance analysis considering the observed interactions was conducted to compare the different methods (M1 – M4). The planning of the scope of random samples for the ash contents was based on a one-sample t-test at a significance level of 0.05 and a power of 0.9, at which differences at the level of half a standard deviation were to be revealed. The calorific values (higher heating value, HHV) of the fresh material and the wood chips after storage were examined for significant differences via Welch's t-test. Using a covariance analysis and a downstream t-test, the moisture content on the north and south sides and on the pile crest on platform P2 were compared (SAS Version 9.4, SAS Institute Inc., USA).

Results

Raw material properties

The particle size distribution (Figure 3.5A) of the material of both platforms (P1/P2) showed that the fine wood chips had a content of fines of 11.5%. They therefore fell into class P31/F20 (Figure 3.5B). The HHV of the wet biomass increased only insignificantly from 18.1 MJ kg^{-1} (± 0.6) to 18.3 MJ kg^{-1} (± 0.2) ($p = 0.0992$) over storage time.

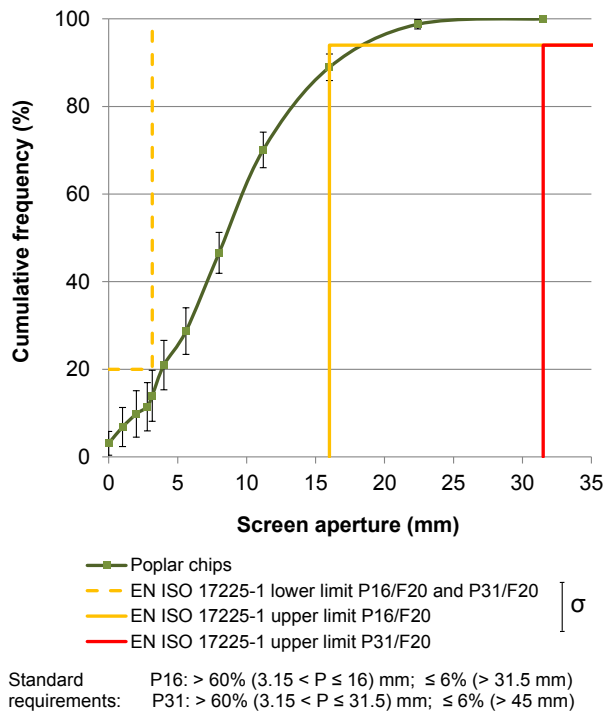


Fig. 3.5A: Particle size analysis of the wood chips

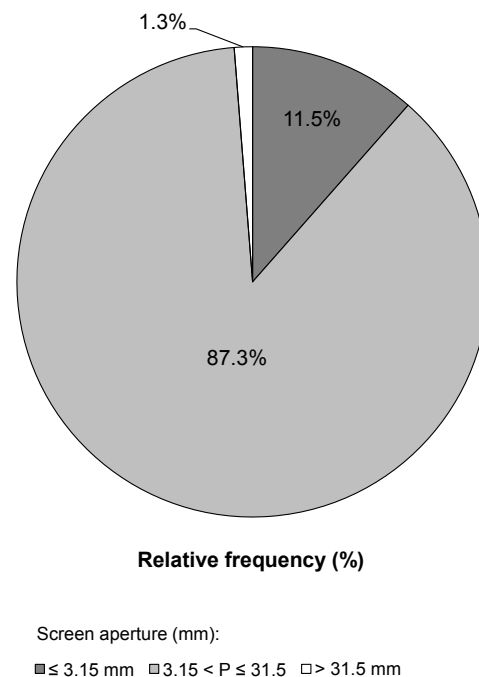


Fig. 3.5B: Mass percentages in the wood chip class P31

Weather conditions

During the 228-day storage period on P1 and P2 at the same location, records showed a mean ambient daily average temperature of 15.2°C , and a total precipitation of 318.5 mm (Figure 3.6).

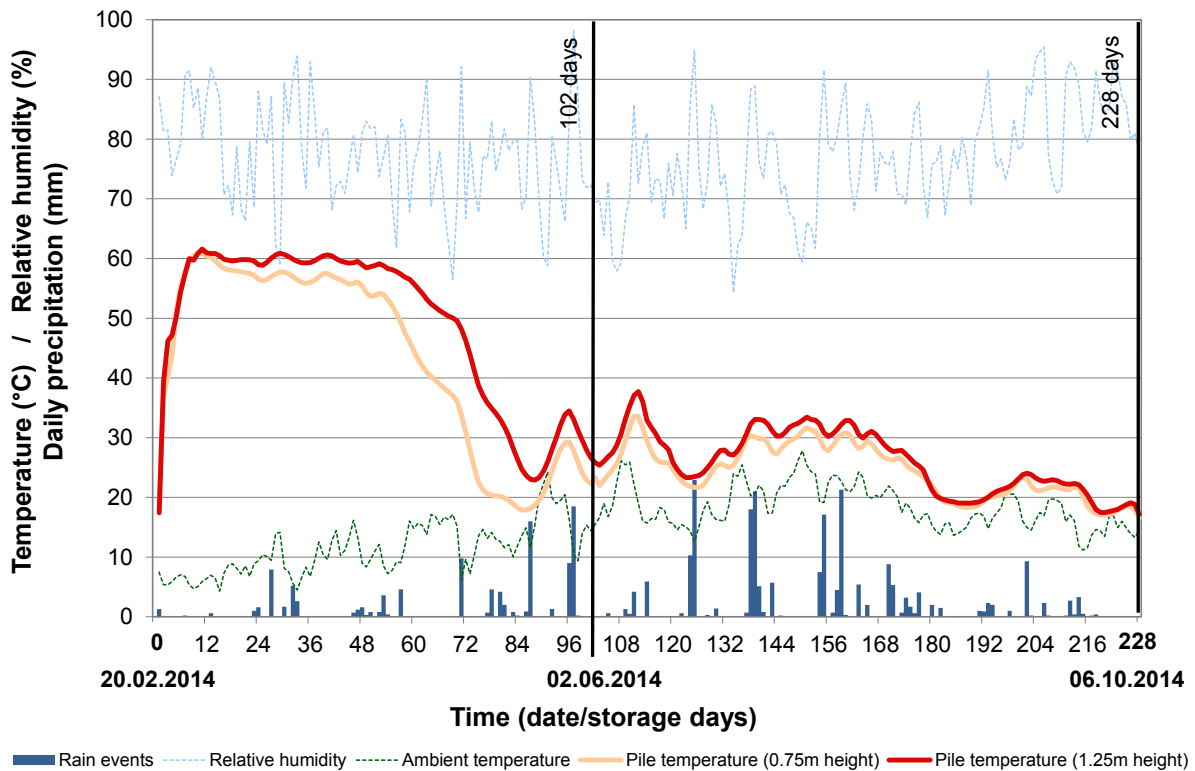


Fig. 3.6: Weather conditions and pile temperatures during storage of fine wood chips on platform P1

Analysis of the long-term mean (1985 – 2014) of the German Meteorological Service's weather station in Potsdam [DWD, 2016] indicated that the year 2014 was a relatively favourable drying year, with an average daytime temperature of 11.0°C and a precipitation total of 409.1 mm for the trial period.

After the wood chip piles were established, the temperature at both measuring heights (P1: 0.75 m / 1.25 m) began to rise to a maximum value of 61°C on day 10 (Figure 3.6). Differences in temperatures between the two measuring heights in the pile on platform P1 can be seen in the first storage phase (day 0 – 102), where the temperature in the core at a height of 1.25 m is slightly higher and remains in the “high temperature phase” ($\geq 50^{\circ}\text{C}$) for two weeks longer than at the lower parts of the pile (height 0.75 m) [PARI ET AL., 2008]. In the second storage phase (day 102 – 228), the two curves align with each other and follow fluctuations in ambient temperatures.

Moisture contents

The freshly harvested wood chips had a mean moisture content of 62.0% (± 0.4), as measured on 20th February 2014. The P1 and P2 piles contained 29.8 and 28.7 tonnes, respectively. Therefore, on platform P1, this corresponded to a mass of 18.5 t water and 11.3 t dry matter. At the end of the storage period, the average moisture content in the pile

cross-section (M3) dropped to 35.3% (± 10.8), giving a corresponding water mass of 5.3 t (Figure 3.7).

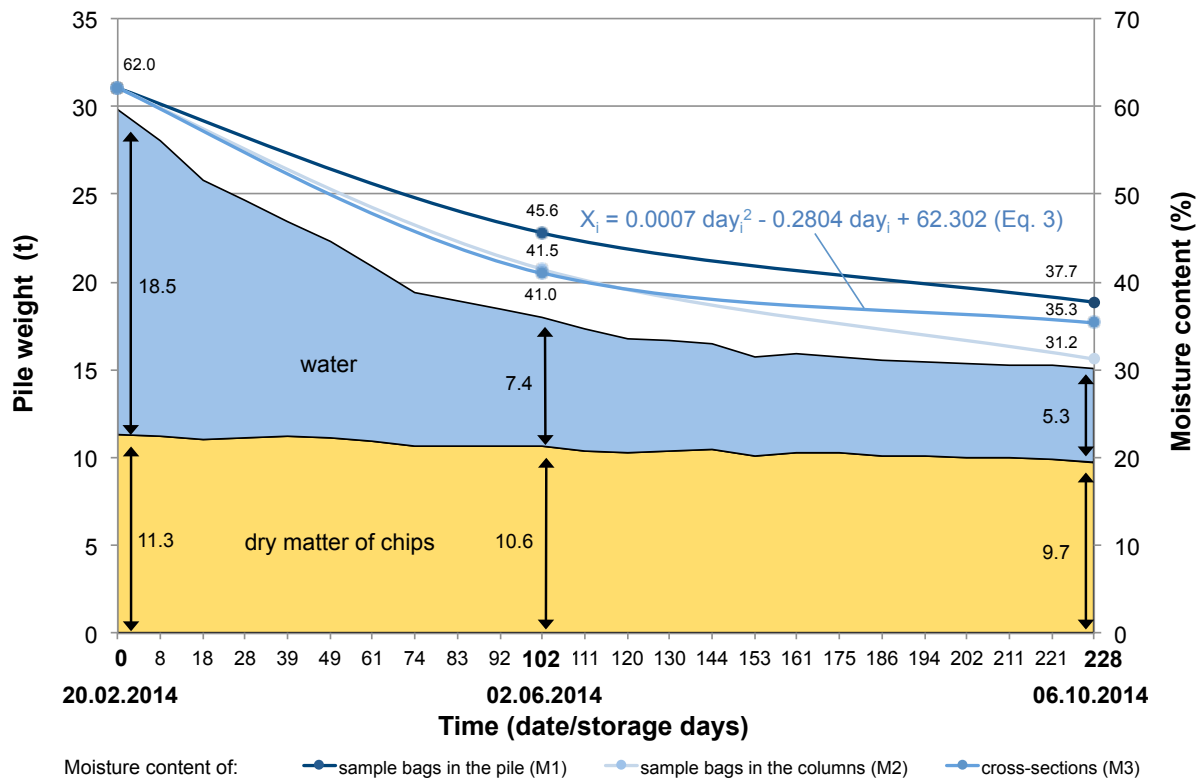


Fig. 3.7: Change in the moisture contents of different samples (M1, M2, M3) and distribution of dry matter and water of the wood chips (M3) on platform P1

Over the storage period on P1, the moisture content of the balance bags in (M2) and outside (M1) the measuring columns dropped to 31.2% (± 7.2) and 37.7% (± 4.9), respectively. The observed high pile temperatures and favourable weather conditions in the summer months potentially promoted the effective drying. Samples taken from cross sections on P1 showed that the standard deviation of the recorded moisture content was 13.4 after 102 days (C1 & C2) and 10.7 after 228 days (C3 & C4, Figure 3.8), indicating that the moisture distribution within the heap became more homogenous as the storage duration increased. The top of the pile, or the pile crest, did not markedly change in moisture content, displaying values of 58.9% (± 11.3) after 102 days and 58.6% (± 10.5) after 228 days.

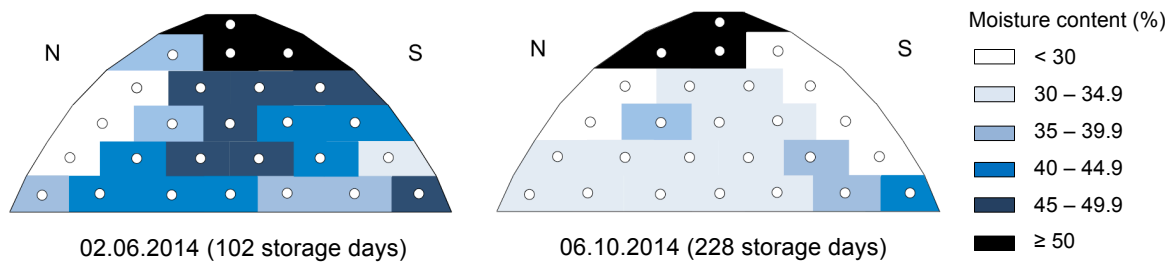


Fig. 3.8: Mean moisture contents of the cross-sections C1 & C2 and C3 & C4 during the storage of wood chips on platform P1

Overall, the moisture content of the upper layer of the wood chip pile fluctuated very strongly over the storage period on P1. In addition, at the end of the storage period there were strong deviations in the wood chip moisture content between the north (± 11.5) and south (± 13.3) sides of the pile, and in the pile crest (± 17.4 , Figure 3.9). The moisture content of the pile crest remained above 40% throughout the entire storage period. The maximum-recorded moisture content was 71.9%, which was higher than that of the freshly stored material.

The detailed examinations of the moisture content in the various upper layers of the pile (0 to 0.6 m) on platform P2 showed that due to the strong scatter of the recorded values, it was not possible to ascertain any layer-dependent differences. Despite this, there were significant differences between the north and south side and the pile crest ($p = 0.0035$, Figure 3.4). On average over the whole storage period on P2, the material on the south side was 7.8 percentage points drier than the material on the north side.

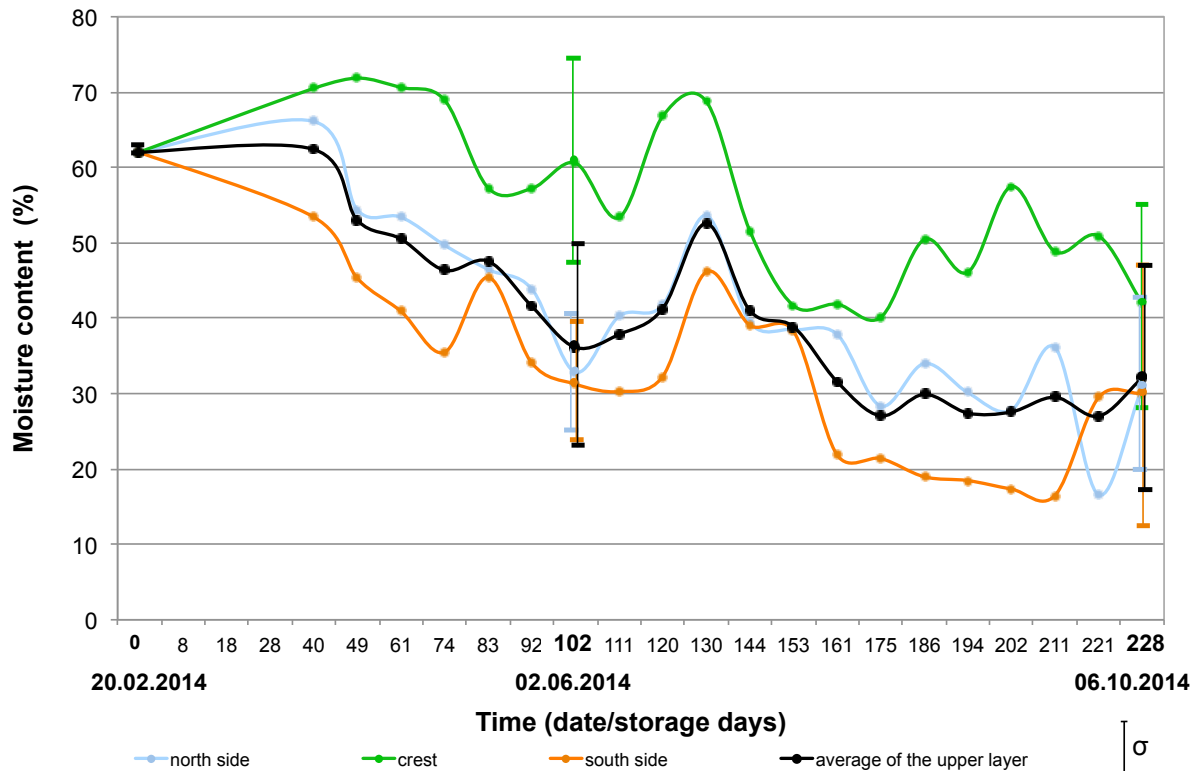


Fig. 3.9: Moisture contents in the upper layer as a function of the sampling location during storage on platform P2

Dry matter losses

Across the four experimental methods, two parameters were used to calculate the dry matter losses that occurred on P1; the moisture content for methods M1, M2 and M3, and the ash contents of the wood chips measured in the M4 method.

At the end of the storage period, after 228 days (converted to months), the dry matter losses determined from changes in the moisture content of samples on P1 were:

M1	23.3% (3.1% / month),
M2	22.7% (3.0% / month),
M3	13.9% (1.8% / month)

and from the ash contents

M4	16.6% (2.2% / month).
----	-----------------------

The statistical comparison of the dry matter losses determined over the entire storage period on P1 using methods M1 – M4 shows that, with slight deviations from the mean value, there is no significant difference between the results of methods M1 (95% CI 22.6 – 24.0%) and M2 (95% CI 20.1 – 25.1%, $p = 0.9997$). There is also no difference ascertainable between the results of methods M3 (95% CI 8.9 – 19.0%) and M4 (95% CI 9.8 – 20.4%, $p = 0.9961$). However, the deviations of methods M3 and M4 from the mean value are distinctly larger (Figure 3.10).

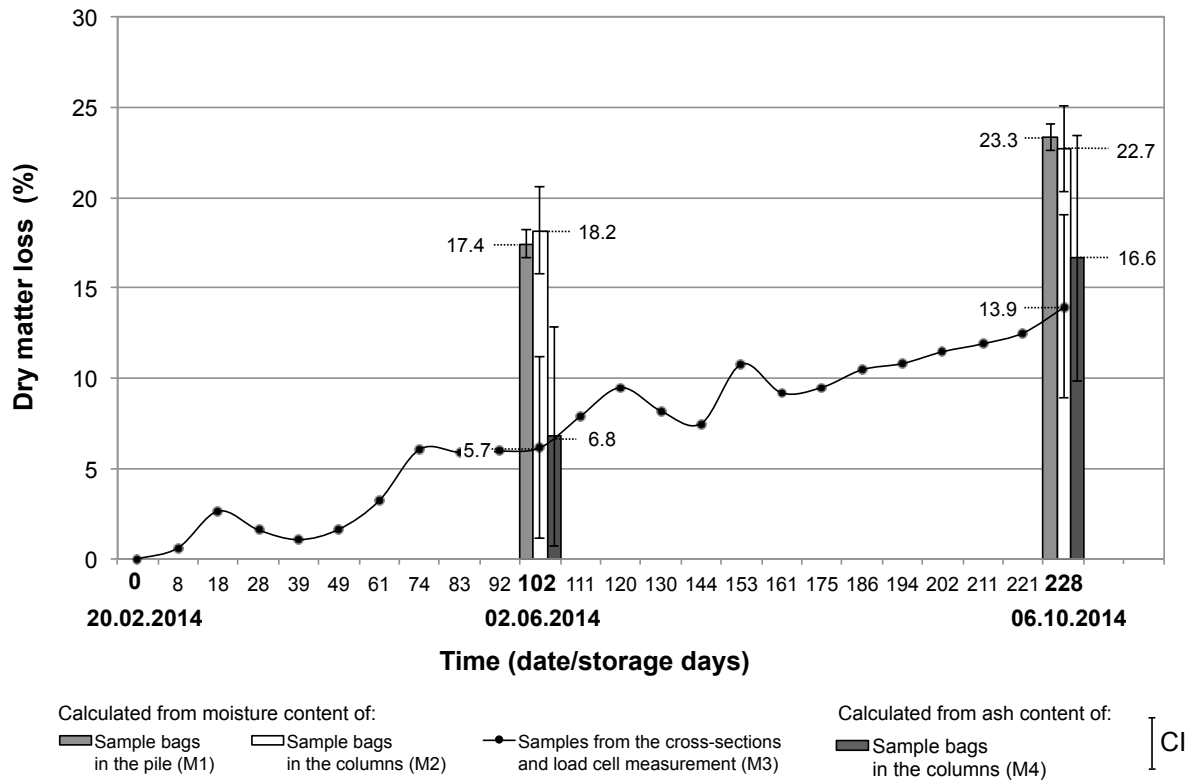


Fig. 3.10: Dry matter losses during the storage of wood chips depending on the method (M1, M2, M3, M4) on platform P1 (95% CI = 95% confidence interval of the average)

The results on P1 of method M1 differ significantly from those of method M3 ($p < 0.0001$) or M4 ($p < 0.0001$). The dry matter losses determined with method M2 also differ significantly from those obtained with method M3 ($p = 0.0002$) or M4 ($p < 0.0001$). Three-quarters of the dry matter losses determined with methods M1 and M2 occur within the first 102 days of storage. By comparison, less than half the total dry matter losses occur then when methods M3 and M4 are used.

Influences on continuous heap weighing results

The weather and the diurnal changes distinctly influence the results of the regular weighing operations on P1, as shown here in Figure 3.11 with an example of variations over a one-week period.

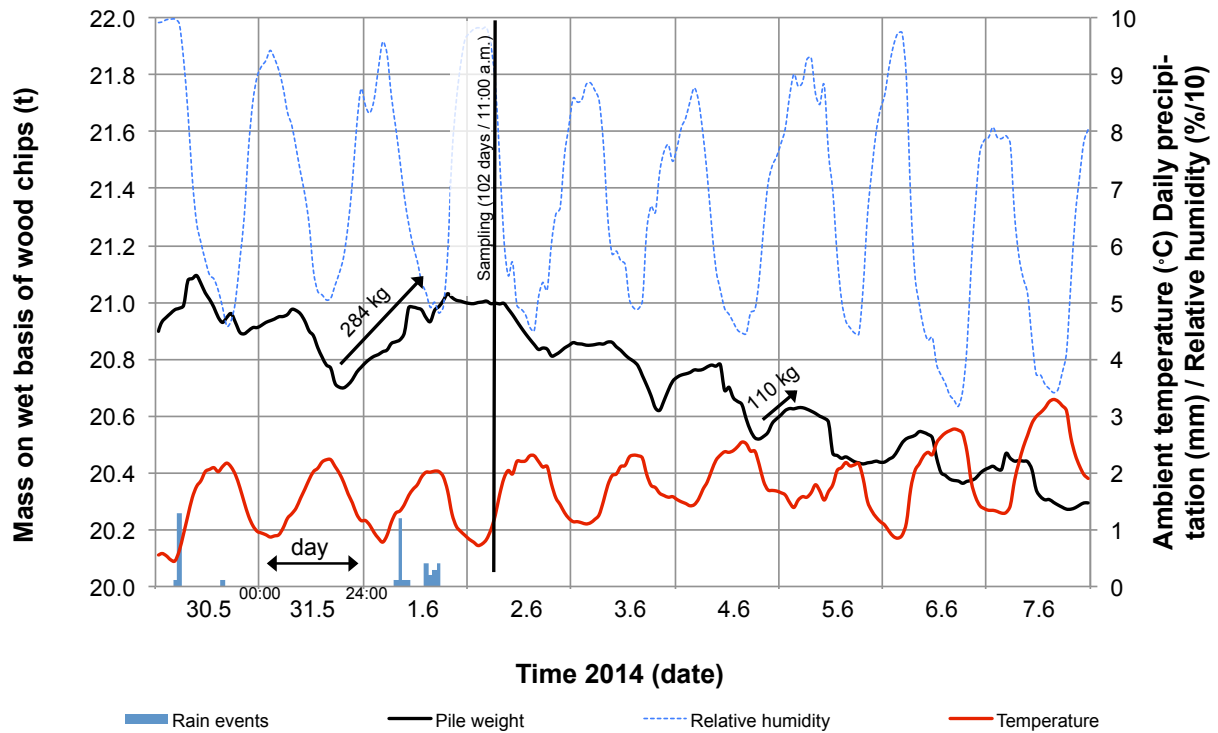


Fig. 3.11: Change in the mass on wet basis of wood chips on platform P1 as a function of the weather conditions showing daily variation

There were daily mass on wet basis fluctuations of approximately 100 kg on platform P1, which always followed the changes in outdoor temperature and relative atmospheric humidity. The low precipitation in the trial period caused only small mass increases that could not be measured after 24 hours. An analysis of the water retention capacity of the covering material showed that an area of 1m^2 of the fleece used in this study can absorb approximately 1.3 litres of water. Therefore, it is hypothesised that the fleece absorbed approximately 50% of the 2.8 mm precipitation on 1st June 2014, and the wood chips absorbed the remainder. In experiments conducted in other regions and at other times of the year, especially with higher precipitation, the weather-related influence could be much higher.

Discussion

Comparison different balance bags methods

In this study, the dry matter losses from storing the same material (SRC poplar) were determined using different methods and compared with the results obtained from the reference method (M1) featuring balance bags distributed loosely in the pile on platform (P1). After a storage period of 228 days, dry matter losses of 23.3% were determined using the reference method (M1) and dry matter losses of 22.7% were detected with M2, which measured dry matter losses from balance bags located in vertical lattice columns embedded in the pile. The results support the hypothesis the M2 method can map occurrences in the cross section well, despite the limited spatial distribution in the pile, and deliver comparable dry matter losses to those of the reference method. Accordingly, the M2 method provides the advantage of a simplified sampling regime whilst causing less disturbance to the pile structure. The monthly dry matter losses of 3.1% (M1) and 3.0% (M2) determined with the two different methods do not statistically differ from each other and are consistent with results reported in literature (Table 3.1).

Ash as a parameter for determining dry matter losses

The analysis method M4 estimates the dry matter losses indirectly by determining the ash content from samples in balance bags arranged in measuring columns in the pile core at different times during storage. The dry matter losses occur due to the breakdown of organic constituents of wood and are associated with a rising ash content after storage [GEJDOS ET AL., 2015]. In this experiment, the dry matter losses calculated using method M4 were 16.6% after the 228-day storage period (or 2.2% / month), therefore provide an underestimation of the result obtained with reference method M1 by 23.3% (or 3.1% / month).

Two studies by BARONTINI ET AL. (2014) and PARI ET AL. (2015) determined the dry matter losses in poplar heaps over the respective periods of 6 and 4 months. They recorded dry matter losses of 14% [BARONTINI ET AL., 2014] and 10% [PARI ET AL., 2015], respectively, with the aid of balance bags. BARONTINI ET AL. (2014) measured the dry matter losses separately for crowns and trunks. The average dry matter loss of 14% was calculated assuming a crown-trunk-ratio of 50:50. If the M4 method is applied to their results, then Equation 3.2 calculates a dry matter loss of 6% [BARONTINI ET AL., 2014] and 20% [PARI ET AL., 2015], respectively. Two other studies by GEJDOS ET AL. (2015) and WHITTAKER ET AL. (2016) weighed the entire wood chip pile before and after storage and determined total dry matter losses of 2% [GEJDOS ET AL., 2015] and 21% [WHITTAKER ET AL., 2016], respectively. If the dry matter losses were recalculated using Equation 3.2 and the observed changes in ash

contents, losses of 10% [GEJDOS ET AL., 2015] and 0% [WHITTAKER ET AL., 2016] would result. In the latter mentioned study [WHITTAKER ET AL., 2016], it should be noted that only 10 samples representing the whole heap were taken, which may not be sufficient to detect the relatively small changes in ash content occurring in other studies with larger numbers of 30 samples [LENZ ET AL., 2016]. The before mentioned calculations indicate that using the measured ash contents to determine dry matter losses (M4) does not systematically overestimate or underestimate dry matter losses compared with the reference method (M1), but instead under-/overestimates on a case-by-case basis. This "unsteady behaviour" might partly be caused by the heterogeneous composition of the stored material. According to LENZ ET AL. (2016), apart from contaminations in the harvested material, the ash content increases substantially with a rising proportion of bark within the samples. The content of bark is generally an undesired component in biomass as it contains considerably more nitrogen, sulphur and ash than the woody component [FILBAKK ET AL., 2011]. The relative wood-to-bark ratio in the wood chip mixture is subject to strong natural fluctuations, which in turn ensure that, depending on the sample, there are large deviations in the ash contents determined. This is reflected in the calculation of the dry matter losses using ash as a parameter.

In order to be able to use the M4 method to calculate dry matter losses, where there were major deviations in the ash content from the measured mean value (95% CI 9.8 - 20.4%), at least 44 samples would be needed to statically detect a difference between samples, based on a significance level of 0.05 and a power of 0.9. Accordingly, the large differences between the results of the method using the ash contents (M4) and the reference method (M1) can be explained by the fact that the number of samples ($n = 10$) selected was too low.

Periodic weighing of the wood chip pile on platform P1

An important and novel aspect of this study is the method for determining the dry matter losses by means of periodic weighing of an entire heap. The dry matter losses calculated by periodic weighing and interpolated moisture contents (from M3) after 228 days of storage are on average at 13.9%, with a monthly mean of 1.8%, and thus are lower than that estimated by reference method (M1, 23.3%, 3.1% / month).

Table 3.1 shows that only few studies have determined dry matter losses from wood chip storage by means of weighing the entire pile. Whereas MANZONE ET AL. (2013) published comparatively low monthly dry matter losses of 1.6% for stored poplar wood chips; BARONTINI ET AL. (2014) cite values of 2.9%. The reasons for differences between the two studies may lie not only in the differing pile sizes (6 t fresh matter vs. 35 t fresh matter, respectively), but also in the low number of samples used for determining the moisture

content (4 and 24, respectively). This is because with this method, precise and representative accounts of the moisture content is crucial for accurately determining the dry matter losses.

The large difference between the results estimated by methods M1 (23.3%) and M3 (13.9%) is presumably attributed to the fluctuations of the moisture content across samples of the heap. In this study moisture content measurements were taken only twice from the cross sections in the pile, mainly because a higher sampling frequency would increase the chances of critically disturbing the pile structure. At the end of the storage period, the calculations were based on a mean moisture content (from cross sections C3 & C4) of 35.3%. This results in dry matter losses of 15.3% (C3) and 12.5% (C4) respectively, giving a difference in dry matter losses of 2.8 percentage points.

The number and location of the samples required for a representative determination of the moisture content can lead to major deviations in the calculation of the dry matter losses, especially when the wood chips have a high moisture content at the start of storage. This becomes particularly evident when there was 1% error in measurement of the moisture content at the time of the first weighing (after storage for eight days), which would result in overestimation of dry matter losses by 2.5 percentage points. The influence of moisture content reduces as the wood chips dry: assuming a similar error at the end of the storage period would result in an overestimation of the dry matter losses by 1.2 percentage points.

With a lower estimated dry matter loss by 9.4 percentage points, the M3 method displays the largest deviation from the reference method (M1). One explanation for this could be that the moisture content of the upper layer of the pile was insufficiently represented by the samples taken. Comparing the moisture content of samples from the upper pile layer on platform P2 with the values measured exclusively from the surface on platform P1 (Figure 3.3: 2, 5, 9, 14 = north side; 1 = pile crest; 4, 8, 13, 19 = south side) showed, however, that the moisture contents were in fact slightly overestimated. The drying rate of the entire top layer (0.6 m) of the wood chip crest was very inhomogeneous and was strongly influenced by weather conditions and pile orientation.

Conclusions

Balance bags stored in a vertical measuring column (M2) estimated dry matter losses similar to those obtained with balance bags distributed in poplar wood chip piles (M1/reference method). The M2 method represents a sampling methodology with a distinct reduction in measuring effort compared with M1, especially for periodic measurements.

It is possible to determine dry matter losses of a wood chip pile from monitoring changes in the ash content of samples (M4). In view of the naturally variable relative compositions of wood and bark, a considerably higher number of samples per sampling event is necessary in order to obtain statistically supported results from a wood chip pile on a practical scale. Under the test conditions described, 44 samples, instead of the 10 taken in this study, would have been necessary to account for the majority of the variation in the samples.

The challenge with utilising a relatively simple method for determining dry matter losses by weighing a complete pile (M3) lies in identifying a representative moisture content to the weighed mass. The large number of samples needed to determine an accurate moisture content distributed across a highly heterogeneous pile is labour intensive and expensive, and cannot be carried out without disturbing the pile. If effective and simpler equipment for determining the moisture content, e.g. using sensors or probes could be utilised, this method would represent a suitable alternative for determining dry matter losses.

The drying profile and the development of the dry matter losses within the upper layer of the pile (on platform P2) could not be examined sufficiently with the test design used. In future, balance bags should also be incorporated in the upper pile layer, so that the entire wood chip pile can be examined.

In order to achieve optimal drying progress in the pile surface in practice, it is recommended that the pile crest be aligned in a north-south direction.

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General discussion

The present study focused on reliable and regular determination of dry matter losses using a newly developed sampling system during storage of wood chips on a practice scale (100 and > 500 m³). With the aid of a fine chip pile and a coarse chip pile, the influence of the chip format on the characteristic storage parameters for pile behaviour (pile temperature, O₂ and CO₂ concentration, calorific values, ash content, moisture content, dry matter loss) was analysed regularly in order to examine if coarse chip formats have a positive effect on the storage of wood chips (**Chapter one**). In addition, an alternative method for representative determination of dry matter losses on the basis of the stem base diameter of individual trees and their ash content was developed from the wood and bark components (**Chapter two**). The calculated dry matter losses were compared with the alternative methods on a platform with continuing weighing function as a further method and compared with the balance bag method as a reference (**Chapter three**).

The reliable and regular determination of dry matter losses and further characteristic storage parameters in practice piles during the whole storage period form the basis for identifying the connections in pile behaviour and for drawing conclusions on the interaction of biological-chemical degradation processes. On this basis it would be possible to research the causes of dry matter losses in future and develop measures to reduce these dry matter losses in this current study.

The data on dry matter losses of wood chips from short rotation coppices over an approx. six-month storage period are characterised by strong fluctuations between 7 and 27% [MANZONE ET AL., 2013; BARONTINI ET AL., 2014; PECENKA ET AL., 2014; PARI ET AL., 2015; WHITTAKER ET AL., 2016]. Causes for the differing results in literature are seen to lie in the selection of different tree types/species, chip formats, coverings, pile sizes, sampling, determination methods, storage periods and different storage regions with their varying weather conditions.

In the present study particular cause variables on the storage behaviour of wood chips were explored in greater detail. The focus lay in particular on the influence of **trial design**, **methods** used and **chip formats** used on the determination of dry matter losses during the storage of wood chips.

The investigations for this study were conducted in North-East Germany with poplar wood and the same weather conditions, and accordingly are only directly comparable with the results of other trials in literature using poplar wood within the moderate zone [SCHOLZ & IDLER, 2005; HORVATH ET AL., 2012; PECENKA ET AL., 2014; LENZ ET AL., 2015]. Although many studies using wood chips from poplar have been conducted in Italy too, the results of the

experiments are not transferable due to the completely different weather conditions [BARONTINI ET AL., 2014; PARI ET AL., 2015; MANZONE & BALSARI, 2016].

Trial design

Within the trial design, the study was focusing on the influence of pile volumes and the sampling method on the determination of dry matter losses.

Pile volume

In the trials of SCHOLZ & IDLER (2005) on an experimental scale (10 m³) dry matter losses could be reduced by storing larger chip formats with a maximum chip length of 150 mm. Large chip formats and the resulting large pore volume of the storage pile allow more intensive air flow within the pile, thus accelerating the drying process. After one-year storage of fine chips dry matter losses of 25% resulted, with a moisture content on removal from storage of 35%. In the case of coarse chips the dry matter losses were reduced to 23% and the moisture content on removal from storage was down to 25% [SCHOLZ & IDLER, 2005]. Use of chunks (150 mm) even achieved dry matter losses of only 18% with moisture contents of around 20%. Despite this, studies of such small piles display in general always strong edge effects and the results might not be directly transferable to practice. That is why the current study deliberately examines pile behaviour on a practice scale. Utilising 100 m³ and > 500 m³ chip piles, the study aims to ascertain what minimum pile volume is necessary to survey representative measurement data.

Independently of the storage region and tree species, a typical feature of storing freshly harvested fine chips in unventilated piles is the direct onset of an increase in the pile temperature to approx. 60°C, when harvested at above-freezing temperatures [FERRERO ET AL., 2009; HORVATH ET AL., 2012; MANZONE ET AL., 2013; BARONTINI ET AL., 2014; PECENKA ET AL., 2014]. If fine chips are harvested at frost, the direct onset of pile temperature increase can be delayed by four weeks (**Chapter one**). PECENKA ET AL. (2014) support this statement with results of two storage experiments conducted on a practice scale (> 500 m³) with fine chips from poplar over six and seven months respectively. The authors assume that frozen material is largely storage-stable. Despite of different temperatures at storage intake and storage duration the dry matter losses in both piles have been at the same level at the end of trial [PECENKA ET AL., 2014]. A comparison of the two fine chip piles from **Chapter one** and **Chapter three** of this study showed that the pile temperatures remain in the high-temperature phase ($\geq 50^\circ\text{C}$) for at least six weeks already at a pile volume of 100 m³ upwards. The results in **Chapter three** have also shown that the temperature is highest in the pile core. In the one-year examinations on a 10 m³ scale by SCHOLZ & IDLER (2005), the level of 60°C is hardly reached following the typical rise in temperature after storage intake.

The high-temperature phase is less intensive, lasting only for four weeks and is strongly influenced by fluctuating exterior temperatures. This is made clear by the six-month examinations conducted by HORVATH ET AL. (2012) on the same scale. According to KRISTIN & WETZEL (2016), dry matter losses result from the interaction of microbiological and thermochemical processes and the residual respiration of the wood cells. As these processes are temperature-dependent, it remains to be suspected that the occurrences in the 10 m³ piles do not correspond to those in practice piles. Following the high-temperature phase, the pile temperatures in all piles approach the exterior temperature again step by step.

A key parameter affecting the wood chip quality is their moisture content. Depending on the harvesting year, tree species and clone, the moisture content of the wood chips after harvesting at the same location can differ between 48 and 56% [STOLZENBURG, 2007]. The objective of all wood chip storage for energy production is to achieve a moisture content of around 30% as quickly as possible during storage. Such material is nearly storage-stable. In the one-year studies by SCHOLZ & IDLER (2005), fine poplar chips (10 m³) dried from 60 to 35%. By contrast, HORVATH ET AL. (2012) did not achieve any drying progress after six-month storage of 10 m³ fine poplar chips. The moisture content in the fine chip pile from **Chapter three** (100 m³) was reduced within a nine months storage period from 62 to 31% (samples from columns). In **Chapter one** (> 500 m³), the fine chip pile dried to a comparable extent from 60 to 34% (samples from columns) in seven months. Higher moisture contents of 39% (**Chapter one**) and 35% (**Chapter three**) result if the moister edge areas (samples from the cross-section) are included in the evaluation. In this study, the 100 m³ pile dried faster than the pile over 500 m³ of fine wood chips. In contrary, PECENKA ET AL. (2014) showed that the moisture content of a pile over 500 m³ of fine poplar chips was reduced from 55 to 30% within six months and also from 62 to 33% after seven months (samples from columns). Thus, no direct relationship between pile size and moisture content and the end of the storage could be found. The current study has also shown that drying of wood chips in a pile does not by any means proceed uniformly. While in **Chapter one** (> 500 m³) and **Chapter three** (100 m³) the highest drying progress is reached at the end of the first half of the storage period, the trials by PECENKA ET AL. (2014) only displayed the greatest drying potential within the second half of storage. In all four practice piles the highest drying rate of the wood chips was always towards the end of the high-temperature phase (**Chapter one**, **Chapter three**, PECENKA ET AL., 2014).

Alongside the moisture content, the dry matter losses resulting during the storage of wood chips from short rotation coppices are of high economic importance for the overall system. SCHOLZ & IDLER published a study already in 2005 showing that in one-year storage of fine poplar chips (10 m³), dry matter losses of 25% should be calculated.

Going beyond the results from SCHOLZ & IDLER (2005), this present study illustrated dry matter losses of 23% (100 m³) and 22% (> 500 m³) that after a storage period of eight months (samples from columns). Furthermore, it has been shown that 18% of the dry matter losses have resulted already after four months of storage. However, the condition for this is that the high-temperature phase has already ended. This is also confirmed by the work by PECENKA ET AL. (2014). After four months of storage the dry matter losses in the practice piles only increase slightly (< 5 percentage points).

Storage experiments conducted on a scale of 10 m³ are affected strongly by weather influences and the associated pile edge effects. In order to show the course of pile temperature, moisture content and dry matter loss during storage of wood chips on a representative basis, pile sizes at least of 100 m³ are thus necessary and sufficient.

Sampling method

The level of dry matter losses and moisture contents in wood chip piles can fluctuate depending on the sampling method. Alongside the nature of sample recovery and the number of samples, the area and frequency of sampling does also influence the results. A high number of samples is necessary for a representative description of the pile behaviour, but collecting these also increases disturbance of the pile behaviour. HORVATH ET AL. (2012) did draw at six points in time 6 samples each (n = 6) from piles of just 10 m³ always from the same sampling locations. Although it was easy to do this, each further sample withdrawal did distort the pile behaviour due to the cavities that arise additionally. Although it was easy to do this, each further sample withdrawal led to distortion of the pile behaviour due to the cavities that arise additionally. This alters the sample material and the true pile behaviour is no longer represented. The moisture content and the dry matter losses determined do not correspond to the actual drying progress any more. Due, in recent years the examinations of wood chip piles have been focusing increasingly on the scale used in practice (100 m³ upwards) [AFZAL ET AL., 2010; HEINEK ET AL., 2013; BARONTINI ET AL., 2014; PECENKA ET AL., 2014; GEJDOS ET AL., 2015; WHITTAKER ET AL., 2016]. As the recovery of samples in piles 3 – 4 m high is problematic, sampling nearly always takes place after expiry of the storage period. Here the samples are dug out using heavy-duty machinery [HEINEK ET AL., 2013; BARONTINI ET AL., 2014; PARI ET AL., 2015; WHITTAKER ET AL., 2016]. This generally destroys the pile completely and regular storage monitoring is no longer possible. Regular manual sampling during the whole from the pile surface to determine the moisture contents is limited to a depth of approx. 0.6 m and does not represent the whole pile cross-section (**Chapter three**). Sampling from greater depths or from the inside of the piles is technically not possible without disturbing the pile substantially. Sample drills, such as are used, for example, in

layer-type sampling in maize and grass silos [MCDONALD ET AL., 1991], are also unsuitable given the loose structure of the wood chips.

In the current study a novel sampling system was developed – the use of lattice columns – (**Chapter one**), which enables the recovery of a suitable number ($n = 30$) of samples from different layers of practice piles with greater dimensions without impeding the pile behaviour. Thereby also monthly dry matter losses can be determined representatively for the first time. These results showed that dry matter losses chiefly occur in the first four months of storage.

The number of balance bags to be incorporated in a pile to determine dry matter losses depends less on the pile volume and instead far more on the expected homogeneity of the dry matter losses within the pile, represented as a measured value by the standard deviation and the desired precision. However, the variability of the dry matter losses increases in the case of strong weather influence on piles on an experimental scale (10 m^3). The standard deviation is reduced as the storage period increases. In the trials of the current study in **Chapter one** ($> 500 \text{ m}^3$) and **Chapter three** (100 m^3), the standard deviations of the dry matter losses lie between 2.5 and 4.0 percentage points. At a probability level of 95% and a desired deviation of at most 1.5 percentage points from the mean value, with a standard deviation of 2.5 percentage points altogether 20 samples would be necessary, and in the case of a deviation of 4.0 percentage points as many as 41 samples. The required number of samples would double at each desired deviation of a maximum of 1.0 percentage point from the mean value.

Method to determine dry matter losses

A key focus of this work lay on the question if the method used to determine dry matter losses in wood chips influences the result. The findings of **Chapter three** show that the method of determination does in fact exert substantial influence. Determining dry matter losses in wood chip piles with the aid of balance bags distributed within the pile is still the customary method (reference method) [HEINEK ET AL., 2013; BARONTINI ET AL., 2014; LIN & PAN, 2014; PARI ET AL., 2015; WHITTAKER ET AL., 2016]. This method has also proved successful in other areas of agriculture, such as for example determining dry matter losses in grass and maize silages [MCDONALD ET AL., 1991]. The current study has shown that balance bags in lattice columns do not influence the determination of dry matter losses in wood chip piles (**Chapter three**). Moreover, recovery of the samples was greatly facilitated and regular measurements could be carried out in practice piles for the first time (**Chapter one**), without disturbing the pile behaviour.

In literature dry matter losses are determined alternatively by investigating mass and moisture contents of truck loads of wood chips on storage intake and removal from storage [MANZONE ET AL., 2013; BARONTINI ET AL., 2014; WHITTAKER ET AL., 2016]. BARONTINI ET AL.

(2014) and WHITTAKER ET AL. (2016) compared this method with the reference method (balance bags), and could show that the results differed from the reference method by 4 percentage points downwards and 3 percentage points upwards. The results from **Chapter three** of this study confirm this by a method-related deviation from the reference method of as much as 9% downwards.

The dry matter losses of the three methods stated depend on representative determination of the moisture content. In particular the upper layer of the pile is strongly affected by fluctuating moisture contents due to weather influences, which makes reliable calculation of dry matter losses throughout the entire pile more difficult (**Chapter three**).

Independently of the wood chip moisture content, the dry matter losses determined in **Chapter two** and **Chapter three** were calculated exclusively via ash contents. It must be taken into account that the ash content of bark is six times higher than that of pure wood already on storage intake (**Chapter two**). Therefore the irregular distribution of wood and bark in the wood chips can lead to sampling-related imprecision in determining the ash contents. That is why in **Chapter two** ash contents were determined for the first time on the basis of separately stored wood samples and bark samples. The correct mixing ratio of wood and bark can be determined as a function of the diameter of the stem base of the trees with the equation developed in Figure 2.4 (**Chapter two**). So it was possible to calculate the dry matter losses from these theoretical ash contents. On average the dry matter loss determined from the ash contents of wood chips (**Chapter three**) was 6 percentage points lower during the storage period than the value obtained using the balance bag method (samples from lattice columns). By comparison, when using theoretical ash contents from separated wood and bark samples (**Chapter two**) the deviation was reduced to only 3 percentage points, but in the other direction. This points out that the dry matter losses calculated using the theoretical ash contents of separated wood and bark samples coincide better with the reference method than determining the losses via the ash contents of natural wood chips. Alongside the balance bag methods, determination of dry matter losses using theoretical ash contents of separated wood and bark samples (**Chapter two**) shows as well that dry matter losses during storage of wood chips develop chiefly within the first four months of storage.

Chip format

The storage of coarse (P41) or fine chips (P31) on a practice scale influences the storage behaviour in wood chip piles. This study aimed to examine whether coarse wood chips can reduce dry matter losses and at the same time accelerate drying as shown in studies by SCHOLZ & IDLER (2005) during storage on a practice scale in 10 m³ piles. A further target was

to examine if there is a stringent connection between chip format, pile temperature, and dry matter loss.

Pile temperature

It is evident from the results achieved in **Chapter one** that by contrast with fine chip piles, after the typical onset of increase the temperature in the coarse chip pile only remains in the high-temperature phase ($\geq 50^{\circ}\text{C}$) for a rather short period. This observation coincides with the studies by PECENKA ET AL. (2014), in which the coarse chip pile did not even reach the high-temperature phase. Opposite to this the fine chip pile even reached pile temperatures above 50°C for more than three months. Contrary to the expectations, the dry matter losses of coarse wood chips (21%) were not reduced compared with those of fine wood chips (22%) during the nine-month pile storage on a practice scale (**Chapter one**). PECENKA ET AL. (2014) ascertained dry matter losses of 27% for coarse wood chips and 24% for fine wood chips after a storage period of seven months, even though the pile temperature in the coarse chip pile was distinctly lower. In the seven-month storage of four-year poplars as whole trees (260 m^3), dry matter losses of 7 – 9% occurred even though the pile temperature virtually followed that of the exterior temperature throughout the entire storage period [LENZ ET AL., 2015].

Although high temperatures are characteristic for fine wood chip piles and lower temperatures for coarse wood chip piles, contrary to the statement by SCHOLZ & IDLER (2005) the high pile temperatures from the fine chips do not necessarily result in high dry matter losses.

Moisture content

Moisture contents of around 30% are necessary to be able to use wood chips efficiently. The results of **Chapter one** of this study confirmed the statements by SCHOLZ & IDLER (2005) that storage of coarse wood chips accelerates drying by comparison with fine chips. While moisture contents of coarse chips were 5 percentage points lower after storage for nine months, the chips reached moisture contents of 30% already during the first half of storage. At this point in time the fine chips still displayed moisture contents of 45%. Practical trials with poplar over seven months confirm these results – during the first half of storage the coarse chips dried by 12 percentage points and fine chips by only 3 percentage points [PECENKA ET AL., 2014]. With increasing particle size of the wood chips, the air flow through the pile increases. On the one hand this reduces the pile temperature, while on the other hand it accelerates drying. The whole tree trial with poplar conducted by LENZ ET AL. (2015) showed, however, that despite good aeration with exterior air, 4-year whole trees only dried

from 55 to 42% in seven months. During the winter half year, no further progress was made in drying due to weather conditions.

Accordingly the drying process of poplar wood does not increase steadily with rising chip format. The optimal chip format for drying is presumed to lie between coarse chips and whole trees on the basis of the current results. SCHOLZ & IDLER (2005) achieved optimal drying results with 150 mm long chunks.

Ash content

The ash content is an important quality criterion of wood chips and highly significant for power station operators. On the one hand it aims to prevent slagging of boilers and resulting downtimes. On the other hand a low ash volume is targeted, as its further use – for example as fertiliser or for compensation liming – is heavily regulated and waste disposal incurs high costs of up to 200 €/t [SCHRÄGLE, 2010; SCHRÄGLE, 2015]. **Chapter two** has shown that it is not the chip format, but instead in particular high bark components caused by low stem base diameters that leads to high ash contents. Furthermore, the tree species used play a role [BOJANA ET AL., 2002]. **Chapter two** has shown that the ash content increases along with the dry matter losses during storage. In the case of fine chips, the ash content during the nine-month storage rose by 2.1 to 2.8%, and for the coarse chips from 1.5 to 1.8%. Multiple-stage harvesting procedures and storage of biomass at the edge of the field can also lead to rising ash contents due to the increasing risk of contamination with earth. [EISENBIES ET AL., 2016]. Single-stage harvesting processes like those in this study minimise this risk via direct transport of the wood chips to concrete storage areas.

Calorific values

The calorific values of fuels are generally described with the aid of two values. While the higher heating value (HHV) refers solely to the dry matter, the lower heating value (LHV) also takes the moisture content into account. Alongside the ash content, the chip format of poplar does not have any direct influence on the higher heating value (HHV) (**Chapter one**) either. In **Chapter one** the HHV only increased marginally during storage of both chip formats, for the fine chips by 0.3 MJ kg⁻¹ (18.1 MJ kg⁻¹) and for the coarse chips by 0.2 MJ kg⁻¹ (18.0 MJ kg⁻¹). This fact is also confirmed by the measurements in **Chapter three**, where the HHV rose by 0.2 MJ kg⁻¹ to 18.2 MJ kg⁻¹, and in investigations by JIRJIS (2005) during three-month pasture storage in 6 m high piles of fine and coarse chips in Sweden. Assuming that the HHV increases slightly during storage, it could be suspected that mainly ingredients with low HHV are degraded in the course of dry matter degradation during storage. These include, for example, cellulose (17.3 MJ kg⁻¹) and hemicellulose (16.2 MJ kg⁻¹). This would lead to the relative share of poorly degradable lignin with an HHV of 28.8 MJ kg⁻¹ increasing

and thus the HHV of the wood chips would also increase during storage [HARTMANN ET AL., 2000].

A comparison of the lower heating value (LHV) of the coarse and fine chips reveals a difference, especially after a storage period of 3 months. This is due to the difference in moisture contents between the two chip formats that feeds directly into the calculation of the LHV. At times the better drying of coarse wood chips leads to a 2.0 MJ kg⁻¹ higher LHV. After storage for nine months the LHV in fine chips has increased by 5.7 to 11.1 MJ kg⁻¹, while that of coarse chips has more than doubled from 6.0 to 12.1 MJ kg⁻¹.

For commercial considerations the specific heating value (SHV) has been introduced in this paper for the first time. The SHV considers not only the drying, but also the dry matter losses during storage of wood chips. Although the wood chips have a higher energy quality after storage due to the lower moisture contents, less dry matter is available than at the time of storage intake. For both fine chips and coarse chips, the SHV drops during the storage duration by 0.5 MJ kg⁻¹ (10%). Thus independently of the chip format, in piles covered with non-woven fleece without active aeration, losses of 10% should be calculated.

Gas concentrations

As indicated in **Chapter one**, the concentrations of CO₂ and O₂ during storage of wood chips might be able to supply information about degradation processes. The highest CO₂ concentration (4.2%) and at the same time lowest O₂ concentration (11.2%) of the fine chips was found in the middle of the high-temperature phase at a moisture content of 56% 14 days after storage intake. At this time the dry matter losses were only 6%. In fine chip piles from willow in England, WHITTAKER ET AL. (2016) detected CO₂ concentrations of up to 6.0% already after storage for two days. In Austria HEINEK ET AL. (2013) documented such high CO₂ concentrations in forest wood chips only at moisture contents of over 40%. According to PECENKA ET AL. (2014), high CO₂ concentrations in fine chip piles could be an indicator of low dry matter losses. In a silage clamp (> 500 m³) with concrete sidewalls, only 15% dry matter losses occurred after storage for six months. The moisture content on removal from storage was 30%.

It became evident in **Chapter one** that by comparison with the fine chip pile, the pile with coarse chips was well supplied with oxygen over the entire storage period. The dry matter losses increased constantly during the first four months of storage to 17%. With them, the CO₂ concentration also increased uniformly to 2.9%. At this time, after storage for four months, the O₂ concentration reached its lowest level of 16.9% at a pile temperature of below 40°C. The moisture content was around 37%. It can be deduced from the findings of **Chapter one** and the studies by PECENKA ET AL. (2014) that the dry matter losses in coarse chips occur directly after storage intake, as long as the piles are not frozen, are moist

enough, and are sufficiently supplied with oxygen. According to PECENKA ET AL. (2014), the colonisation by thermophilic mould fungi in coarse chip piles increases directly after storage intake to levels above 10^6 CFU g⁻¹. The population of thermophilic mould fungi in fine chips, on the other hand, remains stable at 10^2 CFU g⁻¹.

Dry matter losses result at pile temperatures between 20 and 60°C. For this reason it can be suspected that the causes of dry matter losses are related to the interaction between several processes. These might possibly be mainly aerobic processes that require moisture contents of more than 40%. Alongside microbiological degradation, for example by fungi which however only become active at temperatures below 40°C, thermochemical oxidative reactions might also be responsible for the occurrence of dry matter losses [SCHOLZ ET AL., 2005; SUCHOMEL ET AL., 2014; KRIGSTIN & WETZEL, 2016].

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General conclusions

In the present study four different methods for the determination of dry matter losses during storage of wood chip piles have been investigated on a practice scale. For the first time storage parameters such as pile temperatures, O₂ and CO₂ concentrations, calorific values, ash contents and moisture contents, and in particular dry matter losses during storage of three practice piles were surveyed and evaluated regularly. The storage behaviour of coarse chips and fine chips was compared. For the first time dry matter losses were calculated via ash contents of theoretical mixtures of wood and bark. A platform with a continuous weighing function served as a further method for determining dry matter losses and at the same time formed the basis for comparing novel methods with the balance bag method as reference. The following conclusions can be drawn from the results of the current investigations:

Method

- Pile sizes of 100 m³ and more are necessary to determine the dry matter losses in wood chips with a statistically sufficient number of samples and repetitions on a representative basis.
- A new kind of sampling system (M2) makes it possible to draw representative samples for determining dry matter losses in practice piles with the help of lattice columns. For the first time in literature dry matter losses can be determined regularly during storage of wood chips with the aid of balance bags without influencing the pile behaviour. This new sampling system has proven successful during several experiments at practice scale. Moreover further diverse storage parameters can be determined in the same way in order to obtain indications of the causes of dry matter losses. In future, the content of wood ingredients, such as extractive substances, cellulose, hemicellulose and lignin, should also be analysed throughout the storage period.
- The number of balance bags to be installed for the determination of dry matter losses is less dependent on the pile size, but on the expected homogeneity of the dry matter losses within the pile, represented as a measurement through the standard deviation and the desired precision. Taking the piles examined as an example, at a probability level of 95% and a desired deviation of at most 1.5 percentage points from the mean value, with a standard deviation of 2.5 percentage points altogether 20 samples are necessary, or with a deviation of 4.0 percentage points even as many as 41 samples. The number of samples required doubles with a desired deviation of at most 1.0 percentage point from the mean value. Based on the statistical analysis in this study no advices regarding the required number of samples can be given in dependence to the pile size.

- Dry matter losses can be calculated alternatively via ash contents of woodchips independently of the moisture content. The number of samples required is 44 per sampling date for experiments with similar design at practice scale. Although the calculation via theoretical ash contents from separated wood and bark samples is more labour and time costly, not only fewer samples are required, but also the deviations of the results from the reference method are reduced. The bark content must be calculated depending on the stem base diameter of the trees. The correlation between stem diameter at cutting height and bark content has been determined for poplar clone Max in this study for the first time. Based on this knowledge further investigations regarding this specific poplar clone are eased.
- In future, with the help of the ash contents of the fine component (< 1 mm) after particle screening, it remains to be examined if dry matter losses can be calculated in simplified form by this method. According to the result from the analyses of ash and bark contents in this study it can be assumed, that there is a significant correlation between the ash content in the fines and dry matter losses. Such correlation described by an appropriate model approach (including e.g. tree variety and clone, stem diameter at cutting height, chip format, moisture content) could deliver results for the dry matter losses with the same precision as method M2 but at reduced costs in labour and time.
- Determining the dry matter losses via a platform with weighing function has not yet proved successful, as the representative and continuous determination of the moisture content is too costly. Reliable moisture sensors might be able to supply repetitious results in future.

Storage behaviour

- During nine-month storage of poplar wood chips in piles over 500 m³, dry matter losses of over 20% are to be expected of both coarse chips and fine chips.
- The dry matter losses of coarse chips and fine chips develop uniformly during the first four months of storage. Accordingly, data on the dry matter losses in per cent per month is not useful for a storage period of four months onwards. The majority of the dry matter losses are accumulated in the first four month of storage. Later on (month five to nine) the further increase of dry matter loss is very small and fluctuates around the maximum value.
- High CO₂ concentrations in wood chip piles inhibit the occurrence of dry matter losses.
- In future the composition of the air in the pile should be analysed in order to determine the relations between further gas concentrations and the dry matter losses.

- Storing coarse chips produced at a theoretical chip length of 75 mm accelerates drying in comparison with fine chips (theoretical chip length 30 mm). Presumably chunks with a theoretical chip length of 150 mm could promote even better drying behaviour.
- In contrast to the assumption from current storage practice in heating plants, the higher heating value (HHV) has not increased with storage time. The HHV remained largely constant during storage, rising only slightly. It could be assumed, that any increases of the heating value due to an increase of the proportion of lignin in the samples is counteracted by simultaneously increasing ash contents. The mechanisms behind this have to be clarified in additional storage experiments including chemical analysis focusing on changes of cellulose, hemicellulose and lignin contents during storage.

Practice

- One prerequisite for good chip qualities are stem base diameters of 15 cm upwards and thus low ash contents of the trees. Consequently cultivation of short-rotation coppices with medium to longer rotation is to be recommended (5 – 10 years rotation, in dependence to the site specific growing conditions).
- The specific heating value (SHV), introduced here for the first time, is to be recommended for commercial considerations as it takes both drying and dry matter losses into account. Given the drop in SHV of 10% for both chip formats, the immediate use of freshly harvested wood chips avoiding any storage is recommended.
- For piles with a volume of 100 m³ and more, no connection could be established between pile size and drying behaviour at the time of removal from storage.
- To reduce dry matter losses during the storage of wood chips, it is advisable to create conditions that greatly delay or prevent the degradation of biomass. Conventional methods used in agriculture should be reviewed for this, such as for example adding lactic or propionic acid, liming, fumigation with CO₂, drying or cooling.
- In order to obtain the best drying results a north-south alignment of the pile ridge is always recommended.
- Using a fleece to cover the pile is effective, as it reduces the ingress of rainwater but still allows water from the pile to evaporate.

Basically it can be concluded that the introduction of the novel sampling system has worked well and that for the first time it has been possible to determine dry matter losses regularly during storage of wood chips. Using this method it will be possible in subsequent studies to

draw samples in order to record changes in the respective hemicellulose, cellulose and lignin components and thus develop conclusions on biomass degrading processes. With this knowledge it will be possible to research methods of reducing these degradation processes on a laboratory and practice scale.

General summary

Establishing short rotation coppices represents an alternative and sustainable land use concept for farms. Harvesting of these fast-growing trees for use in energy applications takes place in January – March with moisture contents between 50 and 60%. The wood chips have to be stored for more than six months as the demand for fuel from biomass power and heating plants is low in spring and summer. Microbiological and chemical degradation can lead to dry matter losses of up to 30% during the storage process, which poses a risk to the profitability of the entire procedure. The distinct causes of dry matter losses have not yet been clarified, as so far there have not been detailed, reliable studies on a practice size scale and strong, method-related fluctuations restrict the informativeness of past results.

The aim of the current research project was to quantify the process of dry matter losses of wood chips during storage in practice-scale piles reliably, and for the first time regularly, in order to be able to draw conclusions about the interaction of microbiological and chemical degradation processes via the relations between characteristic storage parameters in future. Therefore the four research packages had to be addressed:

1. Development of a new sampling system for wood chip piles on a practice size scale in order to be able to determine storage parameters, especially dry matter losses, reliably and regularly (**Chapter one**);
2. Examination of the advantage of coarse wood chips over fine wood chips in regard to their faster drying with lower dry matter losses during storage in practice piles (**Chapter one**);
3. Development of an alternative method for the simplified determination of dry matter losses in wood chip piles on the basis of ash contents (**Chapter two**);
4. Use of a platform with continuous weighing as a further method of determining dry matter losses, comparing them with the results of alternative methods and contrasting them with the balance bag method as a reference (**Chapter three**).

In **Chapter one** a storage trial with two piles, covered by non-woven fabric, with over 500 m³ fine (P31) and coarse (P45) wood chips from poplar was carried out. Ten lattice columns with balance bags were installed in each pile, with the aid of which the storage parameters pile temperature, O₂ and CO₂ concentration, calorific values, ash content, moisture content and dry matter loss were measured or determined each month. On the basis of the results it was possible to compare the storage behaviour of the two piles. By comparison with the fine chip pile, the coarse chip pile showed a short and less intensive high-temperature phase ($\geq 50^{\circ}\text{C}$) with sustained good oxygen supply above 16%. The highest CO₂ concentrations in the piles of 4.2% (P31) and 2.9% (P45) were determined in the middle of the respective high-temperature phase. Contrary to the experience gained in the experimental scale trials in

literature, after a storage period of nine months the dry matter losses determined in the two piles in the current study were almost the same, at 22% (P31) and 21% (P45). More than 17% of these losses occurred already in the first four months of storage. However the coarse wood chips dried more quickly and reached moisture contents of around 30% already after five months of storage. At this time the moisture content of the fine wood chips was still more than 45%, and even after a nine-month storage period it was only reduced to 34%. The higher heating value (HHV) remained constant independently of the chip format. The specific heating value (SHV), introduced for the first time, takes both drying and dry matter losses into account and dropped by 10% for both chip formats in the nine-month storage period.

In **Chapter two** the main research focus lay on the utilisation of the storage parameter ash content, with the aid of which dry matter losses were determined in a simplified, alternative way to the reference balance bag method. Due to the achieved results it became apparent that although the ash contents of the wood chips correlated well with the dry matter losses measured using the balance bag method, but fluctuated strongly due to the irregular distribution of wood and bark in the mixture. For this reason separated wood and bark samples were installed in each lattice column and their ash contents were determined individually on each sampling. With the aid of a newly developed equation, the respective wood-to-bark ratio was determined as a function of the stem base diameter of the tree and the dry matter losses were calculated from these theoretical ash contents.

The results showed that the dry matter losses calculated via the ash content reproduce the values obtained with the balance bag method in good quality. The dry matter losses calculated from the theoretical ash contents of separated wood and bark samples displayed the highest correlation with and hence the lowest deviation (3 percentage points) from the balance bag method. However, this method is costly. The actual fuel quality increases with larger stem base diameters and decreasing ash contents, so that cultivation in medium to longer rotation cycles is to be recommended.

In **Chapter three**, with a fine wood chip pile (100 m³) from poplar covered by a non-woven fabric, the dry matter losses obtained via alternative determination methods on a platform were compared, using the conventional balance bag method as a reference. Alongside the methods of determining dry matter losses via balance bags and ash content samples from lattice columns, losses were additionally determined by continuous weighing of the whole storage pile on the platform.

After a storage period of 228 days, the wood chips dried from a moisture content of 62% to a content of 35%. The investigations showed that using lattice columns for simplified sampling reproduces dry matter losses, here at 23%, of the same level as those supplied using the reference method. The calculation via the ash content from natural wood chips, on the other

hand, produced dry matter losses of only 17% – 6 percentage points lower. In order to obtain reliable results it would be necessary to increase the number of samples from 10 to at least 44. This would in turn increase the outlay for performing the work. Given the deviation of 9 percentage points from the reference, determining the dry matter losses via a platform with weighing function did not prove successful. This statement is backed up by results of an analysis of moisture contents in the upper layer of a pile of the same structure that was created in parallel. The basis for reliable determination of dry matter losses by weighing is the assignment of representative moisture content to the pile. However this was not assured due to strongly fluctuating moisture contents, especially in the upper pile layer.

The results of the present study show that with the aid of the developed sampling system (columns), it is possible for the first time to determine storage parameters and in particular dry matter losses in wood chip piles on a practice size scale regularly and reliably. Investigations are to be conducted on this basis in future to examine further storage parameters, such as the changes of wood component ratios (lignin, cellulose, hemicellulose, extractive substances), in order to clarify the causes of dry matter losses and then develop targeted countermeasures.

Zusammenfassung

Die Etablierung von Kurzumtriebsplantagen stellt für landwirtschaftliche Betriebe ein alternatives und nachhaltiges Landnutzungskonzept dar. Die Ernte für die energetische Verwertungsline dieser schnellwachsenden Bäume findet im Januar – März bei Wassergehalten zwischen 50 und 60% statt. Durch die geringe Nachfrage der Biomasseheiz(kraft)werke nach Brennstoff im Frühling und Sommer ist die Lagerung der Hackschnitzel über mehr als sechs Monaten erforderlich. Durch mikrobiologisch-chemischen Abbau können dabei Trockenmasseverluste von bis zu 30% entstehen, die die Rentabilität des Gesamtverfahrens gefährden. Die eindeutigen Ursachen dafür sind bisher ungeklärt, da detaillierte belastbare Untersuchungen im Praxismaßstab fehlen und starke methodenbedingte Schwankungen die Aussagefähigkeit vergangener Ergebnisse einschränken.

Das Ziel der vorliegenden Arbeit war es Trockenmasseverluste während der Lagerung von Hackschnitzeln in Praxismieten zuverlässig und erstmalig regelmäßig zu quantifizieren, um über die Zusammenhänge charakteristischer Lagerparameter zukünftig Rückschlüsse auf das Zusammenwirken biologisch-chemischer Abbauprozesse ziehen zu können. Daraus ergaben sich folgende Teilziele:

1. Entwicklung eines neuartigen Probenahmesystems für Hackschnitzelmieten im Praxismaßstab, um zuverlässig und regelmäßig Lagerparameter, insbesondere Trockenmasseverluste zu bestimmen (**Kapitel eins**);
2. Prüfung der Vorteilhaftigkeit von Grobhackschnitzeln hinsichtlich ihrer schnelleren Trocknung bei geringeren Trockenmasseverlusten während der Lagerung in Praxismieten gegenüber Feinhackschnitzeln (**Kapitel eins**);
3. Entwicklung alternativer Methoden zur vereinfachten Bestimmung von Trockenmasseverlusten in Hackschnitzelmieten auf Basis von Aschegehalten (**Kapitel zwei**);
4. Nutzung einer Plattform mit kontinuierlicher Wägefunktion, als weitere Methode, um Trockenmasseverluste zu bestimmen, sie mit Ergebnissen alternativer Methoden zu vergleichen und der Bilanzbeutelmethode als Referenz gegenüberzustellen (**Kapitel drei**).

In **Kapitel eins** wurde ein Lagerversuch zweier vliesabgedeckter Mieten mit jeweils über 500 m³ Fein- (P31) und Grobhackschnitzeln (P45) aus Pappel beschrieben. In jede Miete wurden neun Gittersäulen mit Bilanzbeuteln eingebaut, mit deren Hilfe jeden Monat die Lagerparameter: Mietentemperatur, O₂- und CO₂-Konzentration, Heizwerte, Aschegehalt, Wassergehalt und Trockenmasseverlust gemessen bzw. ermittelt wurden. Auf Basis der Ergebnisse konnte das Lagerverhalten beider Mieten miteinander verglichen werden. Dabei

war die Grob- im Vergleich zur Feinhackschnitzelmiete geprägt von einer kurzen und weniger intensiven Hochtemperaturphase ($\geq 50^\circ\text{C}$) bei dauerhaft guter Sauerstoffversorgung über 16%. Die höchsten CO_2 -Konzentrationen in den Mieten von 4,2% (P31) und 2,9% (P45) wurden in Mitten der jeweiligen Hochtemperaturphase festgestellt. Nach neun Monaten Lagerdauer wurden entgegen der Erfahrungen im Technikumsmaßstab in beiden Mieten fast gleiche Trockenmasseverluste von 22% (P31) bzw. 21% (P45) ermittelt, davon entstanden bereits mehr als 17% in den ersten 4 Lagermonaten. Dabei trockneten die Grobhackschnitzel jedoch schneller und erreichen bereits nach fünf Lagermonaten Wassergehalte um 30%. Zu diesem Zeitpunkt lag der Wassergehalt der Feinhackschnitzel noch bei mehr als 45% und reduzierte sich auch nach neun Monaten Lagerdauer nur auf 34%. Der obere Heizwert (HHV) blieb unabhängig vom Hackformat konstant. Der erstmalig eingeführte spezifische Heizwert (SHV) berücksichtigt neben Trocknung auch die Trockenmasseverluste und sank bei beiden Hackformaten in neun Monaten Lagerdauer um 10%.

Im **zweiten Kapitel** lag der Fokus auf dem Lagerparameter Aschegehalt mit dessen Hilfe alternativ zur Bilanzbeutelmethode und gleichzeitig vereinfacht Trockenmasseverluste bestimmt wurden. Dabei hat sich gezeigt, dass die Aschegehalte der Hackschnitzel zwar gut mit den Trockenmasseverlusten der Bilanzbeutelmethode korrelierten, aber aufgrund der ungleichmäßigen Verteilung von Holz und Rinde im Gemisch stark schwankten. Aus diesem Grund wurden in jede Gittersäule separierte Holz- bzw. Rindenproben eingebaut und deren Aschegehalte zu jeder Probenahme einzeln bestimmt. In Abhängigkeit des Stammfußdurchmessers der Bäume wurde mit Hilfe einer entwickelten Gleichung das jeweilige Holz-Rinden-Verhältnis berechnet und die Trockenmasseverluste aus diesen theoretischen Aschegehalten kalkuliert.

Die Ergebnisse zeigten, dass über den Aschegehalt berechnete Trockenmasseverluste die Werte der Bilanzbeutelmethode qualitativ richtig wiedergeben. Die höchste Korrelation und damit geringste Abweichung (3 Prozentpunkte) zur Bilanzbeutelmethode wiesen die berechneten Trockenmasseverluste aus theoretischen Aschegehalten separierter Holz- und Rindenproben auf. Diese Methode ist jedoch aufwendig. Die Brennstoffqualität selbst nimmt mit größeren Stammfußdurchmessern bzw. sinkenden Aschegehalten zu, wodurch der Anbau im mittleren bis längeren Umtrieb zu empfehlen wäre.

In **Kapitel drei** wurden anhand einer vliesabgedeckten Feinhackschnitzelmiete (100 m^3) aus Pappel die Trockenmasseverluste alternativer Bestimmungsmethoden auf einer Plattform der klassischen Bilanzbeutelmethode als Referenz gegenübergestellt. Neben den Methoden Trockenmasseverluste über Bilanzbeutel und Aschegehaltsproben aus Gittersäulen zu bestimmen, erfolgte die Ermittlung zusätzlich durch kontinuierliche Wägung der Miete auf der Plattform.

Nach 228 Tagen Lagerung trockneten die Hackschnitzel von 62% Wassergehalt auf 35%. Die Untersuchungen haben gezeigt, dass die Nutzung von Gittersäulen zur vereinfachten Probenahme die Trockenmasseverluste mit 23% in gleicher Höhe wie die Referenzmethode wiedergeben. Die Berechnung über den Aschegehalt aus natürlichen Hackschnitzeln ergab hingegen 6 Prozentpunkte geringere Trockenmasseverluste von nur 17%. Um zuverlässige Ergebnisse zu erhalten, müsste die Probenanzahl von 10 auf mindestens 44 gesteigert werden. Dadurch stiege wiederum der Aufwand der Durchführung. Die Ermittlung der Trockenmasseverluste über eine Plattform mit Wägefunktion hat sich mit einer Abweichung zur Referenz von 9 Prozentpunkten nicht bewährt. Diese Aussage stützen Ergebnisse zur Analyse von Wassergehalten in der oberen Schicht einer parallel angelegten baugleichen Miete. Grundlage für die zuverlässige Bestimmung von Trockenmasseverlusten mittels Wägung, ist die Zuordnung eines repräsentativen Wassergehalts der Miete. Durch stark schwankende Wassergehalte insbesondere in der oberen Mietenschicht war dies jedoch nicht gewährleistet.

Die Ergebnisse der vorliegenden Arbeit zeigen, dass mit Hilfe des entwickelten Probenahmesystems Lagerparameter und insbesondere Trockenmasseverluste in Hackschnitzelmieten im Praxismaßstab erstmalig regelmäßig und zuverlässig bestimmt werden können. Auf dieser Basis sollten zukünftig Untersuchungen durchgeführt werden, die weitere Lagerparameter, wie Holzinhaltsstoffe (Lignin, Cellulose, Hemicellulose, Extraktstoffe) aufnehmen, um die Ursachen von Trockenmasseverlusten zu klären und um dann gezielte Gegenmaßnahmen zu erarbeiten.

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