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# Options for Optimizing the Drying Process and Reducing Dry Matter Losses in Whole-Tree Storage of Poplar from Short-Rotation Coppices in Germany

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**Abstract:** For sustainable production of wood in short-rotation coppices and agroforestry systems, it is necessary to optimize the storage processes to achieve low dry matter losses together with low-cost drying. The harvesting of the trees can be carried out very efficiently with modified forage harvesters or tractor-powered mower-chippers. The wood chips produced can be dried naturally at low cost in open-air piles. However, this type of storage is connected with high dry matter losses of up to about one fourth in the course of seven-month storage. Although harvesting whole trees is connected with significantly higher costs, lower dry matter losses are to be expected from storing the trees in piles. Consequently, in this study, the storage and drying behavior of poplar under different German weather conditions and depending on the structure of the storage piles has been examined in detail. After a seven-months storage period, the trees still displayed moisture contents of 41–44% following an initial moisture content of 56% but achieved very low dry matter losses of only 4–7%. Moisture contents of 35–39% could only be achieved in October after a further two-months drying period under favorable weather conditions. All storage piles were built up on approximately 30 cm high support timbers for better ventilation. Additionally, covering the ground with a fleece did not have any influence on the drying behavior, nor did different pile heights. Smaller tree trunk diameters are not only connected with a higher share of bark or ash, but also thinner trunks tend to become damp again more quickly after rainfall. That is why whole-tree storage is suitable above all for medium or longer rotation periods with which, under favorable conditions, the higher harvesting costs can be compensated by a higher wood chip quality and lower storage losses.

**Keywords:** short rotation coppice; poplar; clone Max; storage operation; moisture content; dry matter losses; agroforestry

## 1. Introduction

The production of wood in short-rotation coppices and in agroforestry systems represents a possible way of providing energy and wood raw materials sustainably for the bio-economy, which is becoming increasingly important [1,2]. At present, short-rotation coppices are cultivated on approximately 6600 ha in Germany [3]. For the farmer, many advantages are connected with agricultural wood cropping, such as for example diversification of production with perennial crops [4], improved erosion control and the possibility of building up humus on low-yield locations, and for storing carbon [5–7]. Once the root systems of agricultural timbers such as e.g., poplar (*Populus* spp. L.), willows (*Salix* spp. L.) or black locust (*Robinia pseudoacacia* L.) have become established, these crops are relatively resistant to droughts and can act as an income-stabilizing factor when traditional agricultural crops only supply low economic returns due to weather conditions [7–9]. Furthermore, a reduction in the risk of climate-change-related yield losses in the arable crops cultivated between the agricultural timber strips (e.g., in agroforestry systems) can be achieved due to the reduction of erosion and evaporation [10].

Thanks to their relatively low-cost establishment through cuttings, poplar and willow are among the most frequently selected tree species for wood production in European agriculture by contrast with other tree species such as e.g., robinia/black locusts that require the use of rooted seedlings [11–13]. Depending on the selected planting layout, the rotation period, the intended utilization of the wood and the regional availability of harvesting machinery, harvesting is carried out either via single-stage cut-and-chip methods (rotation period 2 to 5 years), or in two stages via the cut-and-store method (rotation period 4 to 20 years) [14–19]. Independently of the harvesting method and location, the harvest is carried out during the resting vegetation period in winter, as the land is then suitable for driving over if there are frost periods, there is optimal nutrient return thanks to leaf dropping and the transfer of nutrients into the root stock, thus ensuring optimal conditions for regrowth of the root stocks in the following spring [20]. As the trees display moisture contents of 50% and more at the time of harvesting, the harvested material must generally be placed in intermediate storage for low-cost natural drying prior to further utilization [19,21,22]. During this storage period, high weight losses can occur, depending on the raw material properties and the storage conditions. The main causes of these losses are the residual respiration of the living cells following the harvest, microbiological degradation, and thermo-chemical oxidation processes. The detailed mechanisms and interactions of these processes have not yet been sufficiently clarified [23–26].

Trials with whole tree and wood chip storage during the last 20 years have produced very different results regarding dry matter losses per month depending on the wood type and treatment and the storage conditions and storage period, as well as regards to long-term losses (storage duration six to nine months) [27]. Even if the development of the dry matter losses does not follow any linear course as a function of the storage period, a simplified form of dry matter losses to be expected on a monthly basis is often stated. In the case of poplar wood chip storage in open-air piles, these are often in the range of 1.4–4.2% by weight (dry matter) [27–30]. At this rate with a storage period of around seven months, this results in total losses of 10–29% by weight. Under the weather conditions prevailing in Germany from February to October, weight losses of around 20% were determined [24,29,31,32]. At the same time, the wood chips dry during storage in piles. During trials in Germany in recent years, under favorable storage conditions moisture contents of 25% to 35% were determined after a 7-month storage period. Despite this drying, as the storage period becomes longer, mold tends to develop more frequently. This calls for correct handling of the wood chips [23,33–35]. The storage of whole trees too is connected with storage losses. Trials with whole trees or trunk sections from short-rotation coppices have shown that although the storage losses here may be distinctly lower (5% to 9% by weight in an approximately six-month storage period) [32,36,37], in the majority of the trials for which reports are on hand the whole trees dried much more slowly than the wood chip piles depending on the shape of the wood stacks and the weather. Under the weather conditions typical in Germany for the period February to October, moisture contents of 37% to 44% were determined in a number of different trials for the storage of whole poplar trees from short-rotation coppices (storage period six to nine months) [32,38,39]. In 2018 Erber et al. [40] determined very similar results in Austria for storage and drying trials with poplar (39% moisture content, 8% dry matter loss after a six-month storage period). If the whole trees or logs are stored in open-air piles through into the autumn months, they can be remoisturized again in the autumn. In the year 2000, Gigler et al. [37] established that willows stored as whole shoots on the headland of a short-rotation coppice displayed moisture contents of only 18% in August. However, by the end of November, the moisture content had risen to 26% again because of the rain. In the year 2014, Manzone [41] investigated the influence of the position and the diameter of logs stored in a pile on the drying behavior for poplar and black locust in Italy. Smaller logs, as well as logs located in the upper layer of the piles, dried faster in the first month. However, after 6 months of storage a final moisture content of 18–19% was detected with no significant differences between the treatments and wood species. Furthermore, no significant dry matter losses could be detected. Civitarese et al. [42] investigated the influence of the felling date on the drying of whole poplar trees stored in windrows under Italian weather conditions from December to March. Although in some trials dry matter losses of up to 4% have been measured, the statistical analysis showed no significance. A later harvest date showed to be advantageous due to favorable weather conditions for wood drying in spring.

The studies conducted over recent years have shown that in the case of whole tree storage, the dry matter losses and the moisture content depend on a large number of different influencing factors, such as in particular the wood species and the treatment prior to storage, the storage conditions (e.g., pile form and location, the subsoil and possibly the cover) as well as on the weather conditions and the duration of storage.

The essential advantages of whole tree storage of poplar wood from short-rotation coppices are seen not only in the lower losses during storage, but also in the possibility of motor-manual harvesting or harvesting using forestry machinery. This permits harvesting after longer rotation periods (4 to 20 years) with correspondingly larger trunk diameters. Depending on the site location, this can be connected with logistic advantages, such as e.g., greater flexibility in the selection of harvesting time and a reduction in the number of harvests necessary altogether over the entire period of use of an agricultural wood facility. In the same way, the quality of the wood chips produced also increases with the trunk diameter due to a distinctly lower share of bark [27,43], and the trunk sections may already be suitable for material utilization. Essential disadvantages are to be seen in the lower drying of the trunks and the considerably higher harvesting costs [17,18,20]. In order to be able to select the suitable harvesting and storage methods better depending on the site conditions, the behavior of poplar wood from short-rotation coppices during whole tree storage was therefore examined in detail at two of locations in Germany. The following questions were considered in particular here:

- In the case of whole tree storage of poplar, what effect does the stack height have on the weight losses and drying?
- Can covering the soil with a fleece lead to better ventilation, and thus to improved drying of the storage pile?
- Is there a difference in the drying behavior of poplar stems with and without branches?
- What effect do the different weather conditions from year to year have on the storage?
- What influence does the tree trunk diameter have on the storage losses and drying behavior?

## 2. Materials and Methods

Whole-tree storage trials were conducted with poplar (Klon Max-*Populus nigra* L. Authority × *populus maximowiczii* A. Henry) at Potsdam (federals state of Brandenburg) and Schwarzbach (federal state of Thuringia) in the years 2014 and 2017. For this, trees aged 4 or 8 years were harvested manually from short rotation coppices and stacked for a storage trial (Table 1).

**Table 1.** Plantation characteristics and harvest technology.

| Place | Planting Layout | Rotation | Age<br>Years | SDCH [a]<br>cm | Harvest Date<br>dd-mm-yyyy | Harvesting System |
|---|---|---|---|---|---|---|
| Potsdam<br>(52.26° N; 13.01° E) | Double row<br>(2.25 m × 0.75 m × 0.55 m) [b] | 5th | 4 | 7.0 | 03-03-2014 | Manual with a chainsaw |
| Schwarzbach<br>(50.79° N; 11.86° E) | Single row (3.0 m × 1.0 m) [c] | 1st | 8 | 12.6 | 25-01-2017 | Manual with a chainsaw |

[a] SDCH = Stem diameter at cutting height (10 cm) = trunk base diameter; [b] Row distance × inner row distance × planting distance; [c] Row distance × planting distance.

### 2.1. Trial Setup at the Potsdam Site

Following the motor-manual harvest in Potsdam, a 300 m$^3$ pile of whole trees with dimensions 11 m × 10 m × 3 m (width × depth × height) was set up using a telescopic loader (Figures 1 and 2). The pile has been built up on a grassy area and at a sufficient distance from surrounding trees to exclude shading. The measurements of the storage behavior started on 07.03.2014 and ended on 14.10.2014.

**Figure 1.** Manual harvest with a chainsaw.

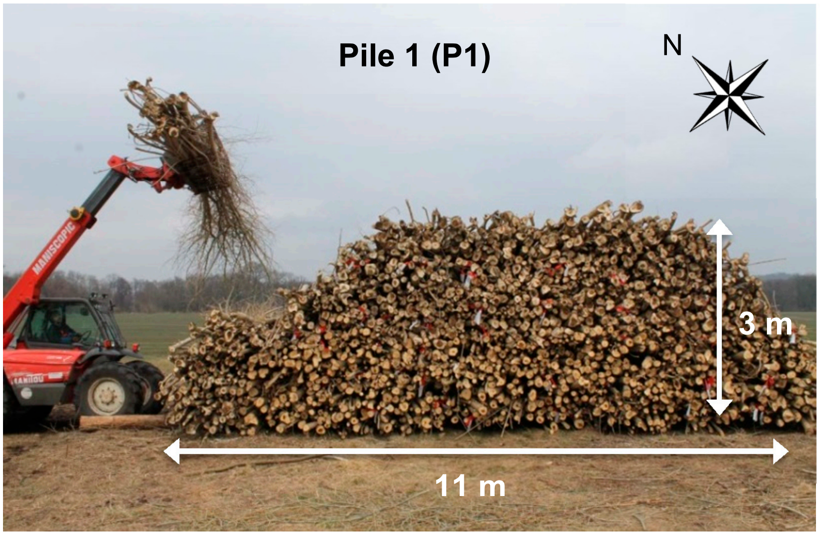


**Figure 2.** Construction of a pile of whole poplar trees with the help of a telescopic loader at Table 1. in Potsdam.

For better ventilation, the pile was constructed on 30 cm thick cross beams. Two sample trees were installed in each of five pile layers (Bottom layer, Intermediate layer IL 1, Middle layer, Intermediate layer IL 2, Upper layer) for each of the 8 sampling dates. Sampling was carried out every 4 weeks. All the sample trees were weighed before storage intake in order to determine the dry matter losses and a representative moisture content was determined with the aid of four comparable trees from the harvested stock using the oven drying method (EN ISO 18134-2). The 4 trees used for the measurement of the initial moisture have been cut into stem sections of 20 cm length and 40 evenly over the tree length distributed samples (2 kg sample weight each) have been chosen. It has been assumed, that the moisture content of these comminuted trees and the sample trees incorporated into the pile were the same at storage intake. For all further analyses (e.g., ash or moisture analyses), mixed samples were prepared from these collected stem sections. Consequently, these samples were always a mixture of the components bark and wood provided with the stem section.

The pile was built up in accordance with the pile scheme shown in Figure 3.

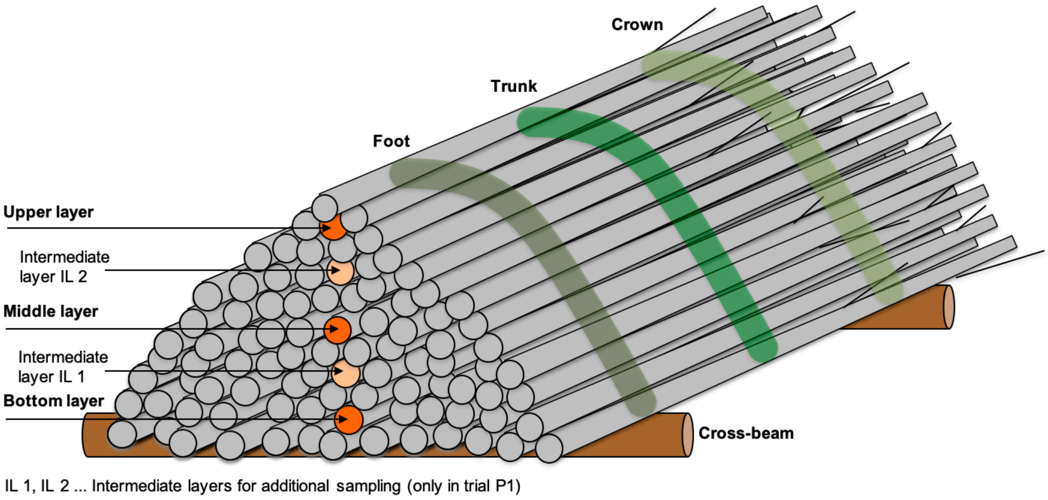


**Figure 3.** Schematic structure of the storage piles and the positions of the measuring levels.

An unaltered sample tree with side branches (P1b) and a sample tree from which the branches had been removed (P1a) were taken into storage in each layer. The sample trees were selected in such a way that the trunk foot diameter and the build of the trees were both comparable and typical of the overall harvest quantity. On the sampling dates, the correspondingly prepared sample trees were withdrawn from the pile using a tractor and analyzed. The moisture content was considered in a differentiated fashion for three tree sections (foot, trunk, crown). For this the trees were divided into three sections of equal weight (Figure 4). This subdivision was determined in a preceding trial. 2 kg of sample material (whole stem sections containing wood and bark) were taken uniformly distributed from each section of every sample tree to determine the moisture content. For this purpose, all sections were cut into 20 cm long pieces and the required amount of sample material was taken.

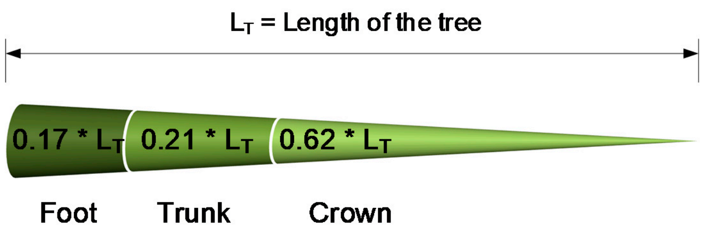


**Figure 4.** Division of the trees into three sections of equal weight.

The calculation of the dry matter losses ($L_i$) taking into account the moisture contents (X) of different wood samples at the time of sampling i was carried out in accordance with Equation (1).

$$L_i = \left(1 - \frac{m_{out,\,i}\,(100 - X_{out,\,i})}{m_{in}\,(100 - X_{in})}\right) \times 100\% \quad (1)$$

| | | |
|---|---|---|
| $L_i$ | dry matter loss at time i | [%] |
| $m_{in}$ | wet mass at storage intake | [kg] |
| $m_{out,\,i}$ | wet mass at time i | [kg] |
| $X_{in}$ | moisture content at storage intake (on wet basis) | [%] |
| $X_{out,\,i}$ | moisture content at time i (on wet basis) | [%] |

It was known from earlier storage trials that freshly harvested and stored poplar sprout strongly even in the pile without root connection and could thus influence the drying behavior. When withdrawing the trees with side branches (P1b), it was assumed that most of the side branches would break off and the balance of the dry matter losses would be falsified. For this reason, taking five typical trees as an example, the average weight share of the branches in the total weight of the trees was first determined. When determining the dry matter losses, the determined branch share of 14.5% (on a dry matter basis) was deducted from the intake weight of the sample trees with branches (P1b). Furthermore, during sampling the remaining branches of these trees were removed completely after withdrawal from the pile and before weighing.

Moreover, the ash contents (EN 14775) of each sample were determined and in addition data loggers were positioned within the pile for continuous temperature measurement. The temperature loggers were on the insides of the pile on a strap in net bags so that they could be recovered more easily when the piles were taken out of storage (Table 2).

**Table 2.** Parameters and methods for analyzing tree samples.

| Parameter | Unit | Number of Samples Per Pile | | Methodology/Specification |
|---|---|---|---|---|
| | | Storage Intake (Trial P1/P2–4) | Per Sampling (Trial P1/P2–4) | |
| Weather conditions | | | | German Weather Service |
| Outdoor temperature | °C | Daily averages | | Potsdam (52.23° N; 13.03° E) |
| Relative atmospheric humidity | % | Daily averages | | for trial P1 respectively Gera Leumnitz (50.52° N; 12.07° E) |
| Precipitation | mm | Daily sum | | for trial P2–4 |
| Pile temperature | °C | Continuous | | Gemini Type Tinytag TGP-4017 (United Kingdom) |
| Moisture content (X) [a] | % | n = 40/20 | n = 15 [b]/18 [c] | EN ISO 18134-2, [44] |
| Dry matter loss ($L_i$) | % | | n = 5/6 | Equation (1), [29] |
| Ash content [d] | % | n = 5/10 | n = 15/3 | EN 14775, [45] |

[a] Defined as moisture mass fraction on wet basis; [b] In each case 3 samples from 5 layers, both from a tree with and a tree without branches; [c] In each case 3 samples from 3 layers from 2 trees without branches; [d] Defined as mass fraction on a dry basis.

### 2.2. Trial Setup at the Schwarzbach Site

The trial setup at the Schwarzbach site was essentially analogous to the approach already practiced in Potsdam (see Figure 3). However, in order to examine the influence of the surface under the pile and the pile height on the storage behavior in greater detail, three different piles were set up (Table 3, Figure 5). The fleece underlay in trials P2 and P3 was intended to prevent plant growth under the piles that would close the ventilation zone between the cross beams (see Figure 3). In order to examine the influence of the pile height, pile P2 was constructed with a difference in height of 2 m to P3 and P4.

**Table 3.** Data on the storage pile structure for trials P1 in Potsdam and P2-P4 in Schwarzbach.

| Pile | Pile Location | Pile Dimensions width × depth × height | Volume | Fleece Underlay * |
|---|---|---|---|---|
| Unit | | m | $m^3$ | - |
| P1 | Potsdam | 11 × 10 × 3 | 300 | no |
| P2 | Schwarzbach | 11 × 14 × 3 | 350 | yes |
| P3 | Schwarzbach | 11 × 14 × 5 | 600 | yes |
| P4 | Schwarzbach | 11 × 14 × 5 | 600 | no |

* Compost fleece underlay of type TOPTEX, 200g $m^{-2}$, Tencate, Austria.

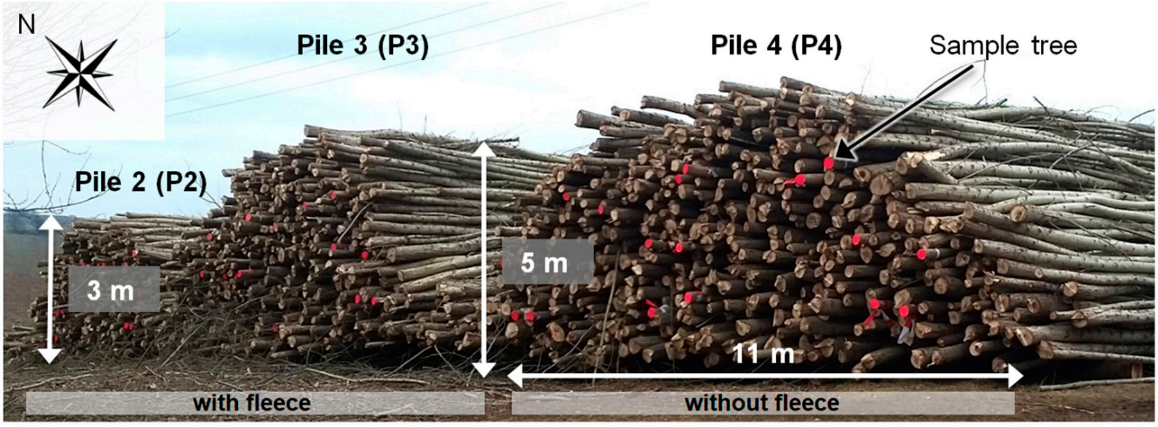


**Figure 5.** Structure of piles of whole poplar trees in trial P2–P4 in Schwarzbach.

The trees for the trials in Schwarzbach were felled on 25.01.2017 and the pile construction was completed on 10.02.2017. As the outdoor temperature during this period fluctuated around freezing point, it could be assumed that the wood mass properties did not change during the pile construction. Only sample trees without branches were installed in the three piles. Storage was carried out for 6 months on the headland of the harvest plot. Two sample trees were withdrawn from three layers (Bottom Layer, Middle layer, Upper layer) of each pile every two months and their moisture content and dry matter loss were analyzed.

### 2.3. Statistical Data Analysis

The statistical analysis was carried out using T-Test to identify significant differences between start and end of trial. The F-test has been used for the analysis of differences between the single treatments at end of storage on the basis of mean values derived from differences to storage intake. A significance level of 5% was specified for the tests (SAS Version 9.4, SAS Institute Inc., USA).

## 3. Results

### 3.1. Weather Conditions Potsdam

The storage and drying of whole trees are substantially influenced by the weather conditions at the respective location. During the 7-month storage period in the year 2014, a mean air temperature of 16.2 °C was determined with only 328.5 mm precipitation (Figure 6). By comparison, the long-term averages of the DWD Weather Station Potsdam in the period from 01.03.–15.10. in the years 1985 to 2014 were 13.5 °C and 397.1 mm. Accordingly, the year 2014 displayed very good natural drying conditions for the trial region. The average relative atmospheric humidity throughout the trial period was 77.3%, though in the last two trial months (15.08.–14.10.) there was a distinct increase to 82.7%. The mean daytime temperature in 2014 was at the same time the highest in the past 30 years.

The temperature data loggers installed in the piles were lost, as the net bags containing the loggers were destroyed by mice. However, the results of the trials in Schwarzbach set out below have shown that the pile temperature and outdoor temperature do not differ much from each other during whole tree storage. Even in periods with rapid changes of weather conditions the maximum differences between pile temperatures and ambient temperature were lower than 2 °C in all trials in Schwarzbach (see Appendix A, Figure A1).

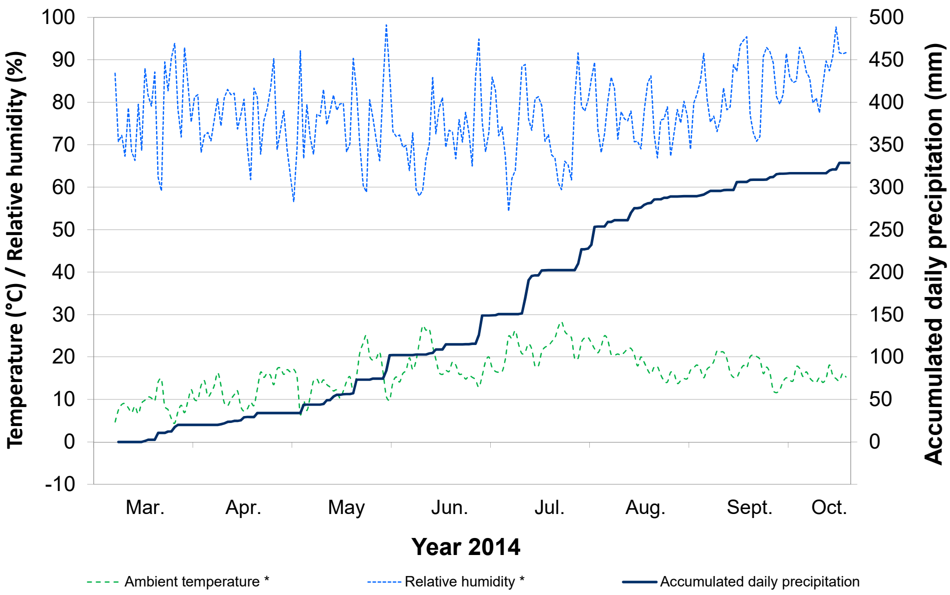


**Figure 6.** Weather conditions and temperature during storage trial P1 in Potsdam (* daily averages).

## 3.2. Weather Conditions Schwarzbach

During the 6.5-month storage period in Schwarzbach, the average air temperature was 12.8 °C and the accumulated precipitation in the trial period was 448.7 mm. Data from the nearby DWD Weather Station Gera-Leumnitz were used to assess the weather conditions in Schwarzbach. The mean daytime temperature and the accumulated precipitation in the period from 15.02. to 31.10. in the years 1988–2017 were on average 12.0 °C and 422.5 mm. Accordingly the year 2017 could be classified as a typical year (Figure 7). The average relative atmospheric humidity throughout the entire trial period was 74.6%. There were still very good drying conditions in the last two months of the trial period (15.08.–14.10.) at the Schwarzbach location, with a mean relative atmospheric humidity of only 76.6%. The temperature measurements in the piles were conducted up to the regular end of the trial in August (see also Appendix A, Figure A1 for temperature data with higher resolution). As the pile was still very damp at this time, the moisture content was established once again in October.

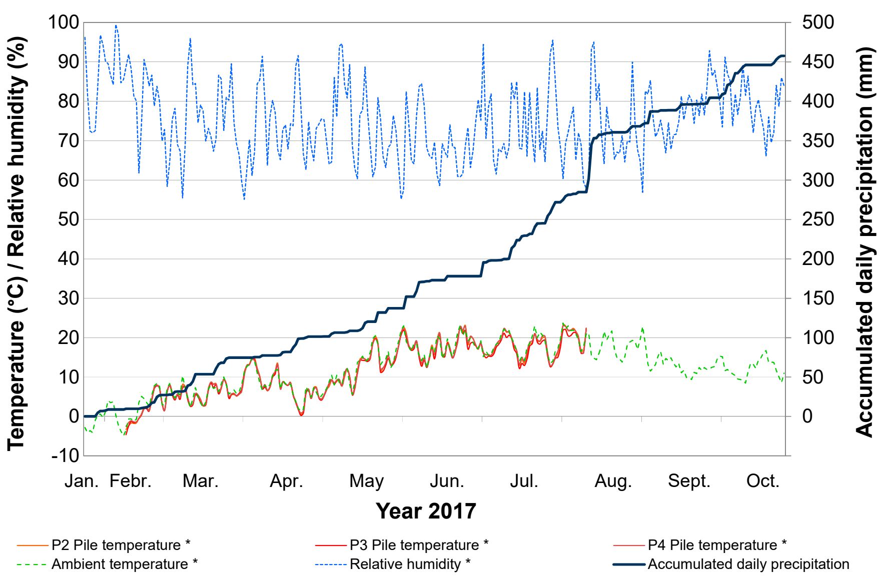


**Figure 7.** Weather conditions and pile temperatures during storage trials P2–P4 in Schwarzbach (* daily averages), cf. Appendix A, Figure A1.

### 3.3. Dry Matter Losses

Table 4 provides an overview of the changes in the material parameters of all piles between storage intake and storage outtake. The development of the dry matter losses and the moisture contents over time are shown in detail in the following Figures 8 and 9.

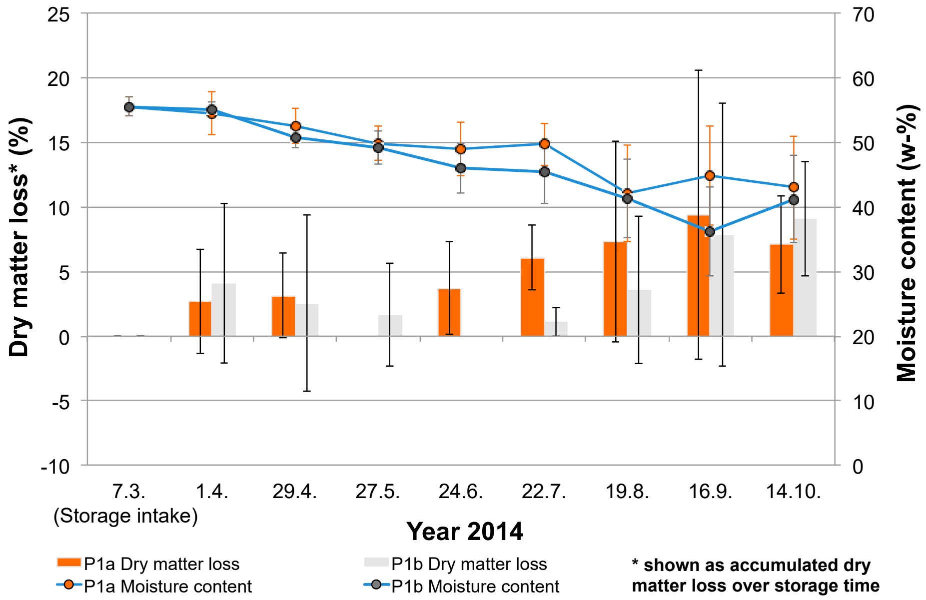


**Figure 8.** Dry matter losses and moisture contents during storage trial P1 in Potsdam (P1a = without branches, P1b = with branches).

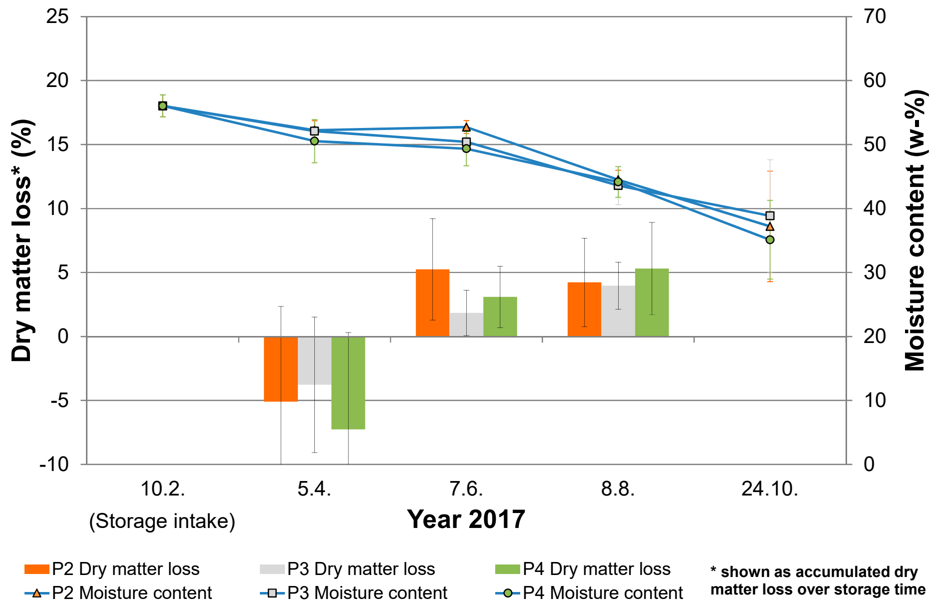


**Figure 9.** Dry matter losses and moisture contents during storage trials P2–P4 in Schwarzbach.

**Table 4.** Overview of mean material parameters (± standard deviation) at storage intake and outtake

| **Material Parameter** | **Dry Matter Loss** | | | | | **Moisture Content [a]** | | | | | **Ash Content [b]** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | % | | | | | % | | | | | % | | | | |
| Pile | P1a | P1b | P2 | P3 | P4 | P1a | P1b | P2 | P3 | P4 | P1a | P1b | P2 | P3 | P4 |
| Storage intake | | | | | | 55.5 ± 1.5 | | 56.0 ± 1.7 | | | 1.76 ± 0.12 | | 1.67 ± 0.16 | | |
| Storage outtake | 7.1 ± 3.8 | 9.1 ± 4.4 | 4.2 ± 3.5 | 4.0 ± 1.8 | 5.3 ± 3.6 | 43.0 ± 8.0 | 41.2 ± 6.7 | 44.5 ± 1.5 | 43.6 ± 3.0 | 44.1 ± 2.4 | | 1.37 ± 0.16 | 1.49 ± 0.11 | 1.47 ± 0.11 | 1.44 ± 0.11 |
| 24.10.17 | | | | | | | | 37.2 ± 8.6 | 38.9 ± 8.8 | 35.1 ± 6.2 | | | | | |

[a] Defined as moisture mass fraction on wet basis, [b] Defined as mass fraction on dry basis, [c] Additional values.

Depending on the sample tree, the dry matter losses fluctuated strongly and in Potsdam after 7 months of storage were 7%–9% (Figure 8). At the end of the storage period no significant ($p = 0.5139$) difference in dry matter losses could be ascertained between the sample trees without branches (P1a) and those with branches (P1b). Consequently, the method of removing branches from the trees prior to storage intake in order to determine the dry matter losses appears suitable. As some sample trees broke when they were being withdrawn and could not be recovered completely, the relevant values for dry matter losses on 27.5. and 24.6 are missing. At no other point in the course of time could significant differences between trees without branches (P1a) and trees with branches (P1b) be observed either ($p = 0.4185$).

After 6 months of storage at the Schwarzbach trial site, dry matter losses of only 4–5% were registered (Figure 9). No significant difference in the losses ($p = 0.7327$) could be ascertained between the three piles at the end of storage. The measured negative dry matter losses in all piles after a storage period of about two months are questionable. Similar results were also determined for storage of wood chips in the first two months (Coarse wood chips size category P63, [28]). The causes for this could not be finally clarified and are to be considered in more detail within the context of the discussion.

### 3.4. Mean Moisture Contents

In Potsdam, the average moisture content of the trees as an average of all layers and over the complete tree length dropped from 55.5% to only 43.0% (P1a) respectively 41.2% (P1b) in the period from storage intake up to the last sampling on 14.10.2014 (Table 4). There was no significant difference ($p = 0.5139$) in the moisture content between the sample trees without branches and those with branches. Accordingly, these values can also be determined in simplified form via sample trees without branches. The whole trees were stored for a further approximately 20 months before the pile was chopped. When the pile was chopped on 29.06.2016, moisture contents of 20.3% were determined ($n = 10$).

A similar picture was found in Schwarzbach. By 08.08., the moisture content dropped from originally 56.0% to 44.5% (P2), 43.6% (P3) and 44.1% (P4) (Table 4). There was no significant difference between the three piles ($p = 0.7055$). Table 5 shows that no difference could be ascertained between the sample trees without branches and the trees drawn additionally with branches either. Generally speaking, the drying behavior of piles P2–P4 appears to be comparatively delayed by comparison with trial P1 in Potsdam. This could be due to weather-related causes, the northern direction of the pile, or the larger trunk base diameter of the trees.

**Table 5.** Drying of trees with and without branches in Schwarzbach (± standard deviation).

| Material Parameter | Moisture Content [a] | | | | | |
|---|---|---|---|---|---|---|
| | Without Branches | | | With Branches | | |
| Unit | % | | | | | |
| Pile | P2 | P3 | P4 | P2 | P3 | P4 |
| 07.06.17 | 52.7 ± 1.0 | 50.4 ± 0.8 | 49.4 ± 2.7 | 47.9 ± 3.4 | 49.7 ± 1.1 | 51.2 ± 1.1 |
| 08.08.17 | 44.5 ± 1.5 | 43.6 ± 3.0 | 44.1 ± 2.4 | 48.1 ± 1.0 | 44.8 ± 3.9 | 44.6 ± 2.8 |

[a] Defined as moisture mass fraction on wet basis.

The three piles only reached moisture contents of 35.1% (P4), 37.2% (P2) and 38.9% (P3) at the additional sampling on 24.10.2017 (Table 4). Despite the different pile structure and partial use of a fleece underlay, no significant difference ($p = 0.3736$) could be ascertained between the moisture contents in piles P2–P4. The comparatively high standard deviations on 24.10.2017 indicate individual drying and degradation behavior of the individual trees.

### 3.5. Drying Behaviour as a Function of Pile Layer and Tree Section

Due to the favorable weather conditions for drying of trees in Potsdam in the year 2014 the drying behavior for the P1 trial conducted there was first considered in greater detail (Figures 10 and 11). Measurements of the same type were carried out in the trials P2–P4 in Schwarzbach. These results are similar and shown in Figures 12 and 13.

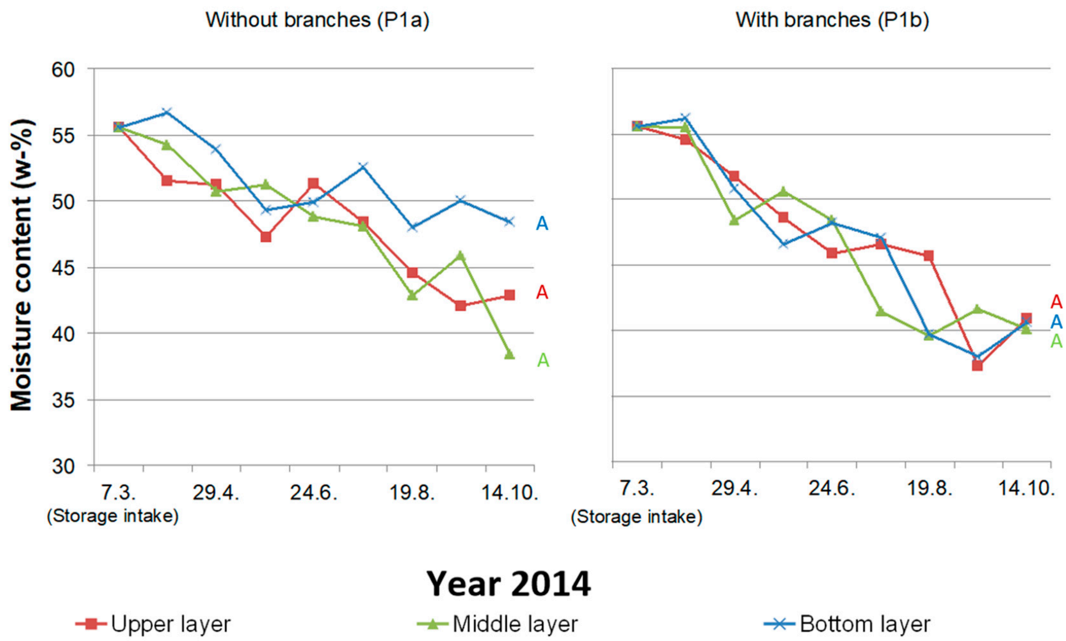


**Figure 10.** Development of the moisture contents in the pile layers for trial P1 in Potsdam (Different letters indicate significant differences between treatments for α = 0.05, F-test).

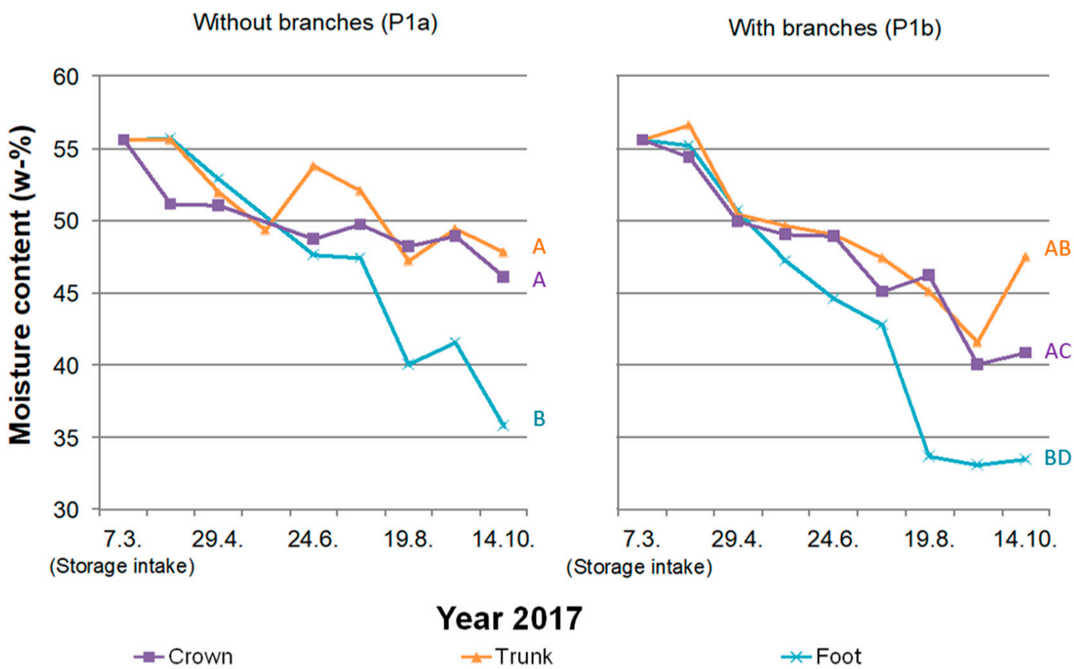


**Figure 11.** Development of the moisture contents for trial P1 in Potsdam depending on the tree section (Different letters indicate significant differences between treatments for α = 0.05, F-test).

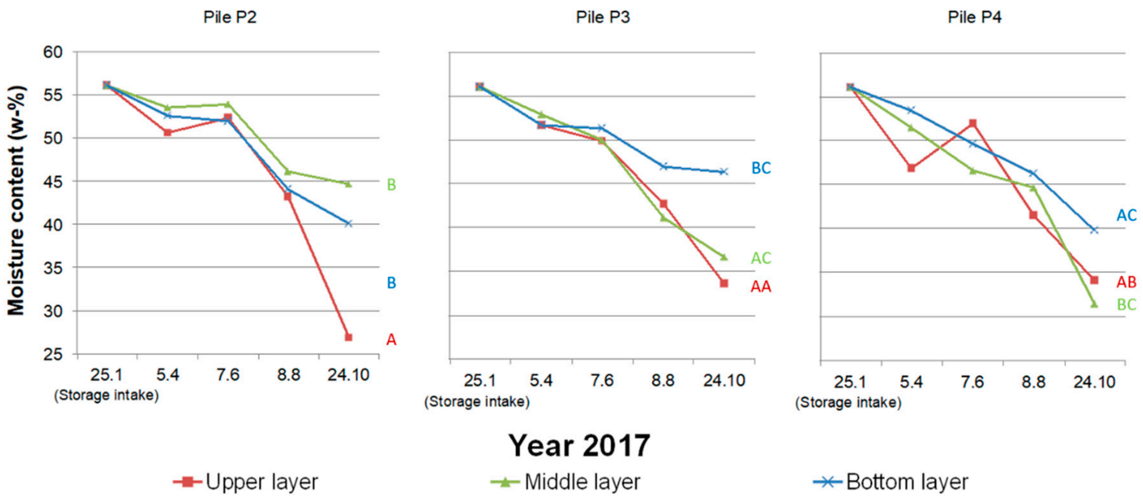


**Figure 12.** Moisture content in Schwarzbach (top - bottom) (Different letters indicate significant differences between treatments for $\alpha = 0.05$, F-test).

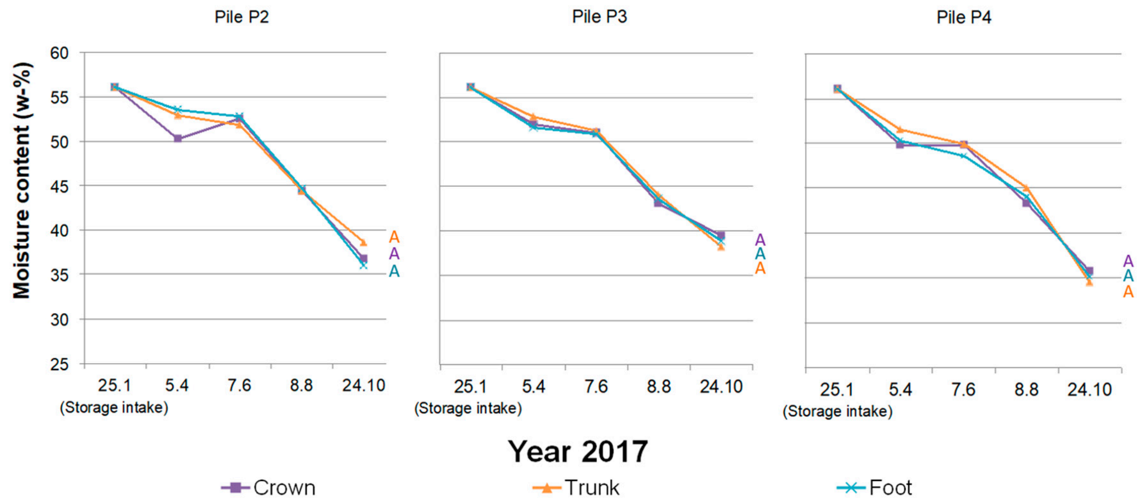


**Figure 13.** Moisture content in Schwarzbach (Foot-Crown) (Different letters indicate significant differences between treatments for $\alpha = 0.05$, F-test).

### 3.5.1. Development of Moisture Contents by Pile Layer

Even when the piles are considered over three layers (Bottom layer, Middle layer, Upper layer), no major difference could be ascertained for trial P1 in Potsdam (Figure 10). Although it appears that the bottom pile layer of the trees without branches dries slower (P1a), no significant differences could be measured. Trials P3 and P4 in Schwarzbach (Figure 12) displayed a similar picture. Only in trial P2 did the upper pile layer dry significantly faster.

### 3.5.2. Development of Moisture Contents by Tree Section

If the moisture contents are considered in differentiated form by tree section, the drying curves show a faster drying of the foot section resulting in a significantly lower moisture content at storage outtake compared to the middle of the tree or the crown in trial P1a/b (Figure 11). This applies independently of whether the sample trees were taken into storage with or without branches. The southerly direction of the pile P1 in Potsdam could have accelerated the drying of the foot section compared to the middle and crown areas. Such clear differences did not become apparent in Schwarzbach (trial P2–P4) due to the westerly direction of the stem sections in this trial (Figure 13).

### 3.6. Ash Contents

The ash content declines as the trunk base diameter increases and the bark share of the trees is reduced (cf. [43,46]). This is also shown by the results of these storage trials (Table 4). As expected, the ash contents of the trees in Potsdam were higher than those measured in Schwarzbach due to the lower trunk base diameter (resp. stem diameter at cutting height, SDCH). The ash content in all piles drops over the storage period. This can be due on the one hand to the bark decomposing during storage, though on the other hand bark can also have been lost due to the strong friction between the trees when they are withdrawn from the piles.

## 4. Discussion

The results of whole tree storage in Potsdam and Schwarzbach have shown that although whole poplar trees tend to dry more slowly than poplar wood chips, they do so with distinctly lower dry matter losses. In order to determine the dry matter losses in the whole-tree piles regularly, therefore, a method of taking samples as smoothly as possible first had to be developed. For this, both sample trees with branches and sample trees from which branches had first been removed were installed in defined pile layers. At the end of the storage period, the results obtained with the two variants from the trials in Potsdam and Schwarzbach are largely comparable. For future trials, it will therefore be sufficient to limit the work to installing trees from which the branches have been removed. Major deviations between the two methods were only found in isolated instances in the course of storage. Here, however, the standard deviation of the individual values is higher than the difference between the sample trees with and those without branches.

In the comparison of the trial sites, Potsdam and Schwarzbach, it is noticeable that although higher outdoor temperatures (16.2 °C to 12.8 °C) and lower precipitations (328.5 mm to 448.7 mm) were documented in Potsdam, despite the southerly direction of the pile the favorable weather conditions were not reflected in lower moisture contents and dry matter losses at the Potsdam site in October. The reason for this could lie in the higher relative atmospheric humidity over the trial period. From 15.08.–14.10. the average relative atmospheric humidity in Potsdam was 82.7%, but in Schwarzbach on the other hand only 74.6%. In this period the pile in Potsdam could have become remoisturized again due to climate-related reasons. The low trunk base diameter of 7.0 cm, the lower pile volume of 300 $m^3$ and the resulting larger specific material surface could have favored re-moisturization. This makes it clear how strongly whole tree storage can be influenced by weather conditions. The range of the detected moisture contents (35–43%) at the end of storage in October is in close accordance to other results from whole tree storage of poplar such as reported by Civitarese et al. 2015 [42] (moisture content at end of storage: 36–45%). The very low moisture contents of approximately 20% reported by Manzone 2015 [41] for 6-month storage of poplar logs could only be reached in the Potsdam trial at a very long storage period of 26 months.

The profiles of outdoor temperature and pile temperature in Schwarzbach did not differ. Accordingly, the temperature behavior in the pile too is determined directly by the prevailing weather conditions. The swift temperature increases up to 50 to 65 °C known from freshly harvested and stored wood chips was not ascertained here [22,27]. A strong temperature increase is an indication of intensive microbiological-chemical processes in the storage pile that can lead to corresponding dry matter losses after relatively long storage [22,25,28]. The absence of this rise in temperature confirmed the very low dry matter losses determined (cf. [41]). The loss of the temperature loggers installed in the pile in the storage trial in Potsdam was thus not relevant, as equivalent measurementthe technical support and the opportunity data from the pile surroundings could be used.

In order to analyze the pros and cons of whole tree storage by comparison with wood chip storage, the storage trial with wood chips (chip size P31, P45 und P63) conducted in the same region (North-East Germany) at the Grunow site (52.15° N; 14.14° E) in year 2015 can be considered [28]. Here medium wood chips (P45) were identified as an optimal chip format for storage on the grounds of their good drying behavior together with comparably low dry matter losses. After 7 months of storage the moisture content of these wood chips dropped to 26.1%. The lowest moisture contents in the whole tree trials in Schwarzbach were still between 41.2 and 43.0% after 8 months of storage and in Potsdam between 35 and 38.9%, after 7 months. The cause for the reduced drying could lie in the fact that the intact bark protects the tree against drying out and so drying chiefly only takes place via the cut surface of the trees at the trunk foot. Wood dries chiefly in the direction of the fibers over the cut surfaces [46]. Chopped wood in the form of wood chips possesses a large number of cut surfaces and a large specific surface area, often without bark, and can, therefore, give off moisture well in all directions. The main advantage of storing whole trees lies in the comparatively low dry matter losses of only 7–9% in Potsdam (P1) and 4–5% (P2–4) in Schwarzbach. However, these losses are still relatively high in comparison to storage trials in Italy [41,42], were no significant losses could be measured for 7-month storage of poplar trees and logs (max. 4%). The storage of freshly harvested wood chips from short-rotation plantations is connected with distinctly higher dry matter losses of at least 17% under the climate conditions of Germany [28,35]. To what extent the higher losses in the storage of the trees in trial P1 are connected with the lower mean trunk base diameters (SDCH = 7 cm) is to be determined in further trials. In trials P2-4, trees with an SDCH of approximately 13 cm were stored. The distinctly low bark share in these trees could be a cause of the much lower losses determined. However, the storage trials conducted by Manzone 2015 [41] showed no significant relation between dry matter losses and stem diameter for wood logs stored under Italian weather conditions.

Storage timbers placed crossways have proved successful in optimizing the design of whole tree stores. They not only ensure better ventilation of the piles, but also prevent weeds from growing into the piles, contamination of stored trees by soil adhesions and soiling of the harvested material by rodents carrying soil into the piles [38,39]. The use of a fleece underlay to cover the soil and the pile height only play a subordinate role with regard to drying.

## 5. Conclusions

If the losses during storage of poplar timber from short-rotation plantations or agroforestry systems are to be minimized, then the storage of whole trees in a pile represents a promising option. Depending on the regional weather conditions, the storage losses can be more than halved by comparison with the usual wood chip storage. An increase in pile height, stem diameter or a fleece underlay showed no significant influence on the drying behavior nor on the losses during storage of whole poplar trees from SRC in a pile.

The associated economic advantage of whole tree storage due to reduced dry matter losses must, however, be compared with the higher costs of the multi-stage harvesting process necessary for the whole tree harvest. Furthermore, it has not yet been clarified how high the additional losses due to a higher share of fines resulting from chipping the trees in a pre-dried state are. For an improved cost-benefit ratio, the process should preferably be applied for harvests in medium or long rotation (rotation period ≥ 8 years). The longer rotation period is not only linked with lower specific harvesting costs. The share of bark also drops and thus the share of fines produced by chipping of dried trees.

The trials have shown that whole tree storage depends strongly on the weather conditions and the occurrence of moisture contents of more than 40% is not unusual after 6–7 months of storage. However, storage with the goal of further drying should not be extended too long into the autumn, as the probability of high atmospheric humidity and the absorption of rainwater will rise further, which can lead to re-moisturizing of the trees. If the trees are to be used in the heating season following on directly from storage, further drying after chipping may be necessary. Alternatively, the wood chips can be mixed with already drier material prior to combustion. Both variants (post-drying, mixing), involve extra costs that must be compared with the cost savings due to reduced storage losses. Thus, further trials on a practical scale that cover all losses (such as e.g., harvest losses, storage losses, losses during chipping) and all costs across the entire process chain from harvesting to use for energy purposes are necessary for a final economic evaluation.

**Author Contributions:** All authors have read and agree to the published version of the manuscript. Conceptualization, R.P., H.L. and T.H.; methodology and experiments, R.P. and H.L.; software and data validation, R.P. and H.L.; writing—review and editing, R.P., H.L. and T.H., funding acquisition, R.P. and T.H.

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**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

## Appendix A

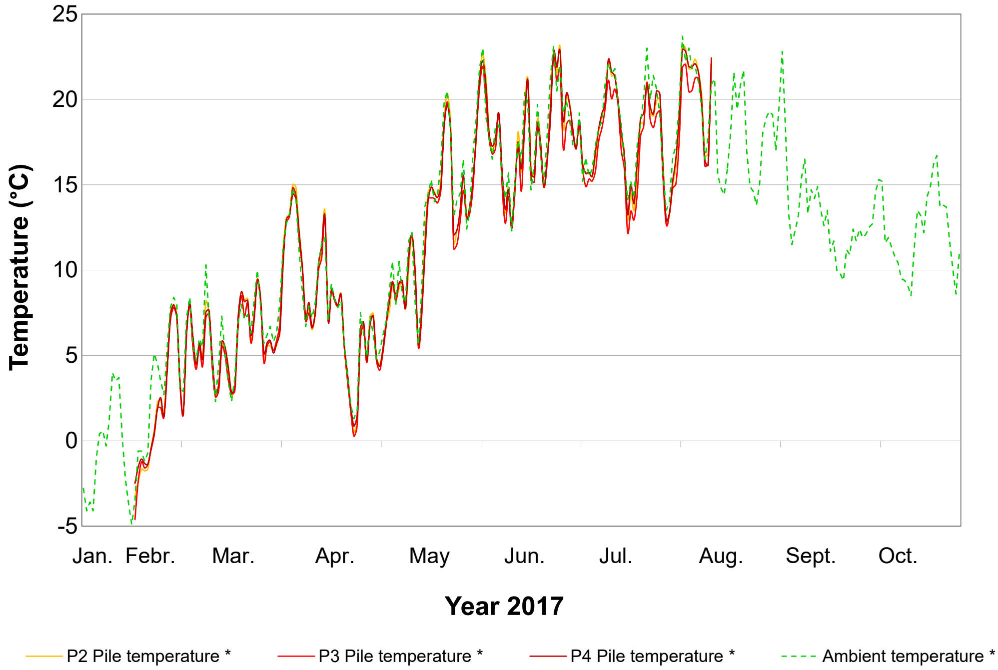


**Figure A1.** Pile temperatures and ambient temperature during storage trials P2–P4 in Schwarzbach. (* daily average).

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