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Within-Stem Differences in Moisture Content Loss during Transpiration and Air-Drying of Felled Oak Trees

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Abstract: This study evaluated within-stem differences in the moisture content of stored summer-harvested oak wood with respect to drying method. The felled oaks were naturally dried for eight weeks, from 4 July to 29 August 2017. We analyzed two methods of preparation and storage: a transpiration drying method (W), and an air-drying method for stem-wood (L). Transpiration drying is a better method for oak stems than air-drying. Statistically significant differences between drying methods were found after six weeks of storage. This coincided with complete wilting of the leaves. However, signs of wilting and leaf color change appeared earlier, between the second and fourth weeks of storage. In parallel, in scenario W, a statistically significant difference in MC of sapwood was observed between the second and fourth weeks of storage. Such a phenomenon was not observed in scenario L. The MC of heartwood also gradually decreased, especially in scenario W. Explanation of this phenomenon lay outside the scope of this study; however, it indicates how the structure and properties of wood, in addition to storage conditions and methods, influence the efficiency of biomass drying in the harvesting area.

Keywords: leaves; wilting; sapwood; heartwood; energy wood; oak wood

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1. Introduction

Wood is a major component of the global renewable energy supply. According to an FAO report, about 50% of the roundwood extracted from forests worldwide annually (or around 1.86 billion cubic meters) is used as fuel: for cooking and heating in households, for small industrial activities, and to a lesser extent for generating electricity [1]. In the European Union, wood is increasingly becoming an alternative to energy produced from fossil fuels. The country with the largest shares of the forest biomass supply (stemwood, primary forest residues, secondary forest residues) in the EU is Germany, followed by France, Sweden, Finland and Poland. Together, these five member states will account for ~60% of forest biomass supply capacity in the EU by 2030 [2].

Sessile oak (*Q. petraea* (Matt.) Liebl.) is an important broadleaved species in Polish forests. In terms of forest area, it is second only to the Scots pine, and thus it is of great importance both ecologically and economically [3]. Oak wood is valued for its durability. In the past, it was used primarily in construction, and it is now used for furniture and valuable veneers. Much of the oak wood is used for energy purposes [4], which is extracted in young stands from whole trees, and in older stands mainly from low quality stemwood and other forest residues [5,6].

The heating value of oak wood is high, mainly because of the high oven-dry density. This property, in addition to moisture content (MC), has the greatest influence on the amount of available heat per unit of fuel. The dry density of sessile oak wood is about 640 kg/m^3 [7], 680 kg/m^3 [8]. High MC reduces fuelwood quality, especially calorific value [9], and has an influence on the economic and environmental aspects of transportation [10]. Predicting and controlling MC can optimize forest biomass logistics [11,12], thereby reducing the carbon footprint [13,14]. Therefore, the first step in preparing fuelwood for use is drying [15,16].

Methods based on natural mechanisms, which are related to the transpiration and hygroscopic properties of wood, are used to reduce MC [17,18]. In practice, to emphasize the differences, distinct names are used for natural drying methods. The drying of whole trees (felled trees left on the ground with their crowns intact) is called transpiration drying (also biological or physiological drying, leaf seasoning, leaf felling, sour felling), whereas the drying of roundwood or chips is often called air-drying [19].

Many factors influence the efficiency of the natural drying process. First of all, the storage time [15,20], and climatic conditions [21]. For this reason, in temperate climates, the best drying conditions are during the summer season [22]. Sometimes after heavy rainfall, but most often in the fall or winter season, the air humidity is high, and the moisture content of the woodfuel increases [23]. Drying efficiency is also affected by the species of wood. Transpiration drying is a most effective method for hardwoods than softwoods, and conversely, air-drying is faster method of drying for softwood than hardwood [24,25]. Another factor influenced on drying process is method of storage [26]. Fuelwood is stored as whole trees, roundwood, split logs or chips. Forest residues and whole trees can by bunched and stored in harvest area or in a pile [27]. Additionally, piles can be covered or uncovered [28,29]. Preparation and storage methods are more or less expensive [30]. For example, split log drying faster than roundwood, but this method is more expensive [31,32].

A very high moisture loss is recorded at the beginning of the storage period because the MC of wood is very high, much higher than the air humidity [19,33]. Once hygroscopic equilibrium is reached, moisture exchange between the material and the environment stops. A similar rule applies to the process of transpiration, which allows the movement of water in the plant [34].

For a certain period after the tree is felled, transpiration occurs undisturbed. The leaves use the water stored in the trunk, which is gradually lost. Later, the water reserves are no longer sufficient, the cells lose their turgor, and the leaves start to wilt. If the period of water shortage is prolonged, the cells in the leaves become irreversibly damaged [34].

For some tree species, transpiration drying is more effective than other methods [17]. Tomczak et al. [35] compared changes in the MC of beech stems stored in a pile and whole trees (felled trees with branches). Over two weeks, the stems stored in a pile lost about 6% of their weight (an indicator of MC changes), while the transpiration-dried energy wood lost about 10%. In another experiment, Saralecos et al. [36] obtained a difference of 6% for Douglas fir. In contrast, the drying of Scots pine stems by transpiration is inefficient [24].

Within-stem differences in MC are significant. Firstly, this is an effect of variation in the density of wood. However, typical radial and axial patterns of changes in the functional or material properties of wood vary greatly between species. Oak is classified in the ring-porous wood category. This group is characterized by relatively high density near the pith [37–41]. Secondly, differences in MC between sapwood and heartwood. Sapwood, as a physiologically active part of the trunk, usually has higher MC than heartwood, especially in coniferous species [42]. In oak, the MC of heartwood is similar to that of sapwood [37], and this may negatively affect the energy value of oak biomass.

This paper compares two methods of drying oak trees for energy purposes. Both methods can be used as short-term or pre-storage, prior to pile storage. In the first scenario (W), we used transpiration drying. In the second (L), roundwood, not cut into segments, was dried. We assumed that drying by transpiration would be a more efficient method in the case of oak logs. In addition, we observed how the MC varied in different parts of the trunk. It was not known how the moisture gradient along the trunk would be affected on the one hand by water loss from transpiration, and on the other by the lack of replenishment and reduction in the deficit by the roots. Moreover, it is well established that water loss occurs mainly at the beginning of storage. Later, the dynamics of the process decrease. The aim of this study was to determine how long the transpiration drying of oak stems should be continued to obtain significant differences, and what the differences would be compared to stems dried without branches and leaves. Additionally, we wished to determine whether signs of leaf wilting would be a good indicator for assessing MC loss.

2. Materials and Methods

2.1. Site Selection, Preparation of Model Trees and Drying Scenarios

The study was carried out at the Murowana Goślina Forest Experimental Station (Poznań University of Life Sciences), Poland. This is a region located in the northeastern part of the natural area of the sessile oak. In this area, oak is an economically important species, second only to pine. A single-species stand of sessile oak (52°32′40.797″ N; 17°4′5.132″ E; 105 m a.s.l.), aged 74 years, was selected (www.bdl.lasy.gov.pl; accessed 4 July 2017).

Data were collected every two weeks from 4 July to 29 August 2017. Model trees were selected by the dendrometric method of Urich, variant I. In accordance with this method, the diameter at breast height (DBH) of all trees selected to be felled for commercial thinning was measured. In the next step, all measured trees were divided into three subclasses according to DBH (14–18 cm, 19–23 cm, >24 cm). For each scenario and storage duration, nine model trees were chosen, three model trees from each subclass. All (n = 72) model trees were felled on the same day.

Two methods of log preparation and storage (drying) were analyzed:

(1) Scenario W: transpiration drying method for felled trees with branches not removed (whole trees);
(2) Scenario L: air-drying method for felled trees with branches removed (stemwood) (Table 1).

Table 1. Characteristics of model trees and summary with total number of samples for the study.

Scenario	Storage Duration (Weeks)	DBH [cm]	Height [m]	Number of Sampled Trees	Number of Sampled Pressler Drill	Number of Samples for MC Estimation
W	2	21.4	18.8	9	67	190
	4	19.0	18.3	9	65	164
	6	19.7	18.4	9	68	172
	8	21.7	19.8	9	67	205
L	2	21.0	18.4	9	71	199
	4	20.3	18.2	9	71	180
	6	20.6	18.9	9	60	163
	8	21.8	18.8	9	72	204
Mean/Total	—	20.7	18.7	72	541	1477

2.2. Weather Data

Temperature, air humidity and precipitation were measured at a permanent weather station of the Murowana Goślina Forest Experimental Station (52°33′12.191″ N 17°6′26.959″ E), about 3 km from the stand in which the model trees were selected.

2.3. Sampling Procedure and Moisture Content Measurement

At the beginning of the experiment (4 July 2017), samples were taken using a Pressler drill (5.15 mm diameter) to determine the initial moisture content (iMC) of the model trees. All samples were taken from the breast height level (Figure 1).

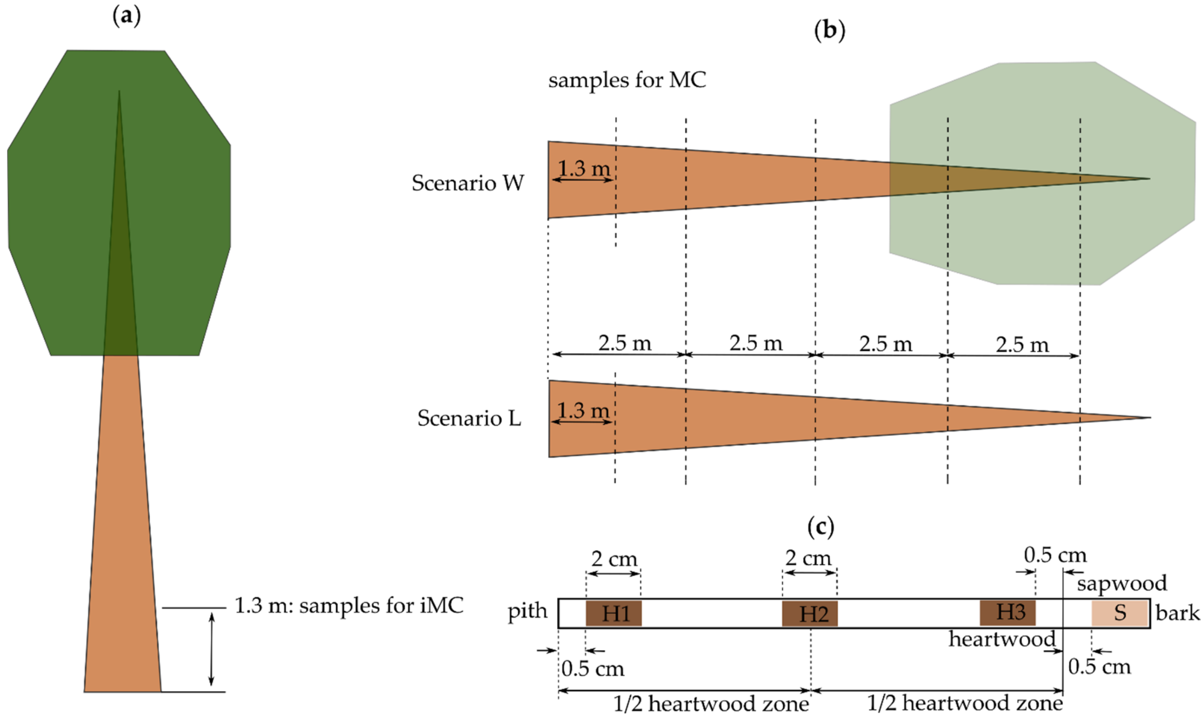

Figure 1. Schematic visualization of the process wood sampling: (**a**) for initial moisture content; (**b**) for scenarios; (**c**) on trunk cross-section.

Then, at two-weekly intervals—on 18 July (2 weeks), 1 August (4 weeks), 15 August (6 weeks) and 29 August (8 weeks)—samples from the model trees were taken for MC analysis. These samples were taken from different parts of the trunk, using a Pressler drill.

The first sample was taken from the breast height level. The next ones were taken along the trunk, up to the apex, sequentially every 2.5 m. The samples were then split into specimens (approximately 2 cm long). The first (H1) was 0.5 cm from the core, and the center of the next (H2) coincided with the center of the section delineating the heartwood zone. The third specimen (H3) was cut 0.5 cm from the boundary of heartwood and sapwood. The fourth (S) was cut from the sapwood. In cases where the length of the sample did not allow all specimens to be delineated, such as when the trunk diameter was small, specimens H2 and H3 were not cut [37] (Figure 1).

The mass of green wood was measured on site immediately after the increment cores had been collected. In the laboratory, the samples were oven-dried at 105 °C. The mass of each sample was measured on an analytical balance (Steinberg Systems SBS-LW-200A, Germany) (±0.001 g accuracy). The absolute MC was estimated using Equation (1):

$$MC = (m_w - m_s)/m_s \times 100 \tag{1}$$

where m_w is the mass (g) of green wood, m_s is the mass (g) of dry wood, and MC (%) is the moisture content.

2.4. Changes in the Conditions of the Leaves

Every two weeks, a sample of 30 leaves was taken from each of the trees that had been cut with intact canopies. After two weeks, there were no clear signs of loss of turgor on any of the trees, and the leaves had no discoloration (Figure 2a). After four weeks, signs of wilting and discoloration were clearly visible (Figure 2b). After six weeks, the leaves were completely wilted and discolored (Figure 2c).

(**a**)

(**b**)

(**c**)

Figure 2. Changes in the condition of the leaves over the time for reducing water: (**a**) 2 weeks after tree felling; (**b**) 4 weeks after tree felling; (**c**) 6 weeks after tree felling.

Each sample of 30 leaves was weighed in green condition immediately after collection. The mass of each sample was measured on an analytical balance (Steinberg Systems SBS-LW-2000A, Germany) (±0.001 g accuracy). We assumed that a change in leaf mass was associated with a loss of water and thus turgor and transpiration capacity. By comparing leaf mass, we aimed to determine in which part of the experiment there occurred the greatest weight loss, which can be considered equivalent to a significant decrease in transpiration.

2.5. Statistical Analyses

In the first step of statistical analysis, the Lilliefors test was performed to determine the normal distribution of the data. When a statistically significant result is obtained, the hypothesis of normal distribution of the data can be rejected. Then, the data between independent groups are compared using the non-parametric Kolomogorov–Smirnov test. If data of more than 2 groups are compared, then Kruskal–Wallis test was used. Statistical inference was performed at a significance level of $\alpha = 0.05$. Calculations were performed using Statistica 13.3PL software (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results

3.1. Weather Data

The average air temperature throughout the period was approximately 18.5 °C. The highest average temperature was observed in the fifth and sixth weeks, between the 29th and 42nd days of storage. Mean air humidity was highest during the third and fourth and the seventh and eighth weeks of storage (Table 2). Heavy rainfall occurred during the experiment, particularly in the second and third weeks after tree felling. For example, on the 21st, 22nd and 39th days of storage the rainfall was about 30 L/m^2, and on the 5th, 9th and 20th days it was about 20 L/m^2. There was also very high humidity, especially in the second and third weeks, on some days reaching almost 100% (Figure 3).

Table 2. Mean temperature, air humidity and rainfall for storage duration.

Weather Data	Storage Duration (Days)			
	0–14	**15–28**	**29–42**	**43–56**
T [°C]	17.5	19.5	20.2	17.1
AH [%]	75	82	76	82
R [mm]	7.8	15.4	10.9	2.0

Note: T—temperature, AH—Air humidity, R—rainfall.

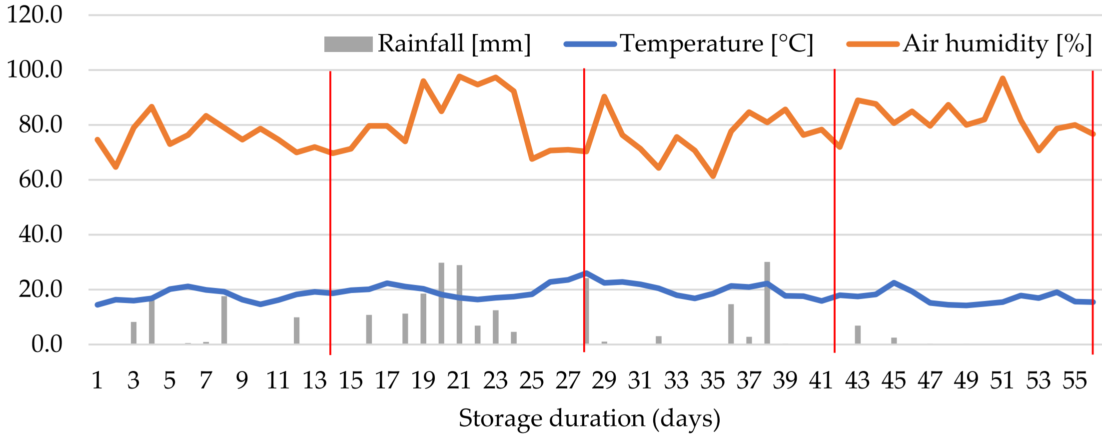

Figure 3. Weather data (daily average).

3.2. Initial Moisture Content (iMC)I

In general, the iMC of the model trees selected to study the effect of transpiration on the drying process (W) was 3% higher than that of the control stems (logs) (L). For different parts of the experiment, differing in the length of the storage period, the differences in iMC were not statistically significant (Table 3).

Table 3. Mean and standard deviation of initial moisture content (iMC), according to scenarios and storage duration (weeks). Samples for iMC analyses from all model trees were collected before felled, on 4 July 2017, at a height of 1.3 m (diameter at breast height).

Storage Duration (Weeks)	Scenarios	
	W [%]	**L [%]**
2	67.68 ± 22.40	57.03 ± 12.15
4	64.05 ± 18.06	58.89 ± 14.88
6	60.81 ± 14.64	65.84 ± 14.26
8	62.54 ± 14.72	60.12 ± 18.26

3.3. Changes in the Weight of the Leaves (Wilting)

On the day on which the trees were felled, the leaf samples weighed 29.39 g on average. After two weeks, the average sample mass was lower by 6.59 g (22.80 g). Four weeks after felling the average mass was 12.97 g, after six weeks it was 12.07 g, and after eight weeks it was 9.65 g. Thus, the greatest decrease in weight was found between samples collected in the second and fourth weeks after tree felling (Table 4). The difference was statistically significant.

Table 4. Changes in the weight of the leaves.

Storage Duration (Weeks)	Weight of Leaves [g]	Weight Changes	
		Absolute [g]	Relative [%]
0	23.39	—	—
2	22.80	6.59	22
4	12.97	9,83	43
6	12.07	0,9	7
8	9.65	2,42	20

3.4. Moisture Content Changes

At each stage of the experiment, the MC of the stems was lower in the W scenario (Figure 4). Two and four weeks after cutting down trees difference between scenarios was about 4 percentage points. At six weeks after the start of the experiment, the difference between scenarios was the largest (about 9 percentage points), and eight weeks was about 3 percentage points. Statistically significant differences between the scenarios were observed sixth (p = 0.000000) and eighth (p = 0.004767) weeks after cutting down trees.

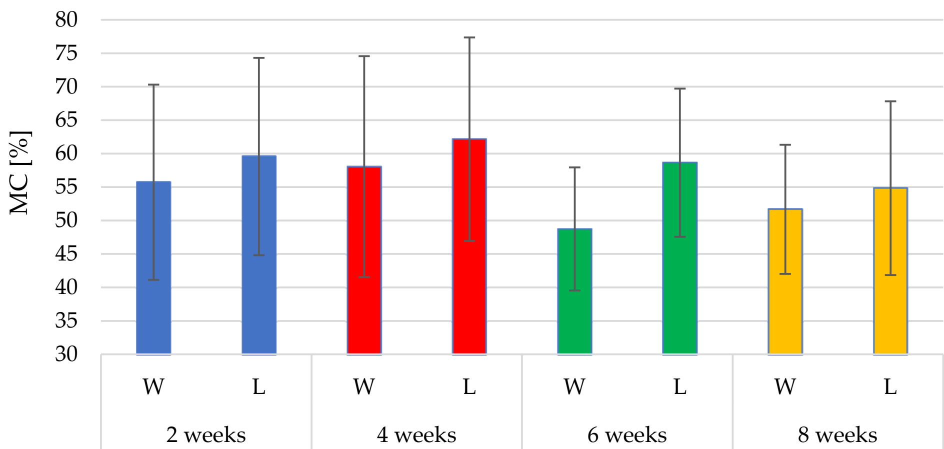

Figure 4. Mean and standard deviation of MC according to storage duration, and storage methods. The average of sapwood and heartwood data. W—scenario W (whole trees), L—scenario L (stemwood).

In scenario W, a statistically significant difference was observed between trees stored two and six weeks, four and six weeks, four and eight weeks. In contrast, in scenario L, storage (drying) time had no effect on MC, and no statistically significant differences were observed.

Six weeks after tree felling, statistically significant differences between scenarios were found for all trunk segments. In the other cases, no statistically significant differences were found (Table 5). However, in each week it was observed that the MC of the segments was lower in the W scenario, especially for the T segment.

Table 5. Mean and standard deviation of MC according to storage duration, storage methods, and tree segments. The average of sapwood and heartwood data.

Storage Duration (Weeks after Cutting Down Trees)	Tree Segment	Scenario W [% ± SD]	Scenario L [% ± SD]	*p*-Value
2	B	57.82 ± 15.05	60.42 ± 15.44	1.000000
	M	56.00 ± 15.64	59.39 ± 13.18	1.000000
	T	49.82 ± 8.70	57.71 ± 15.96	1.000000
4	B	60.71 ± 18.68	65.73 ± 14.51	1.000000
	M	56.69 ± 15.13	59.67 ± 14.92	1.000000
	T	52.39 ± 9.07	57.94 ± 16.00	1.000000
6	B	50.41 ± 8,36	58.61 ± 11.46	0.002557 *
	M	47.60 ± 10.18	58.12 ± 9.52	0.000314 *
	T	46.98 ± 8.51	59.0 ± 13.25	0.042839 *
8	B	53.75 ± 8.79	55.48 ± 11.59	1.000000
	M	49.81 ± 9.40	54.35 ± 14.21	1.000000
	T	50.54 ± 11.15	54.29 ± 13.88	1.000000

Note: * marked effects are statistically significant at $p < 0.05$; B—bottom part of the tree (0.0–5.0 m); M—middle part of the tree (7.5–12.5 m); T—top part of the tree (>15.0 m).

No statistically significant differences were observed for the segments in the W scenario. In the L scenario, a statistically significant difference between sixth and eighth week was observed for the M segment.

In second week of storage, the difference in sMC between the scenarios was approximately 0.6 percentage points. Four, six and eight weeks after tree felling, the differences in sMC between scenarios were higher at 9.7, 10.5, and 5.5 percentage points, respectively. A statistically significant difference between scenarios was observed for fourth (p = 0.007660) and sixth (p = 0.001071) week of drying.

For heartwood, in second week of storage, difference between scenarios was approximately 6.1 percentage points, after four weeks 0.8 percentage points, after six weeks 9.6 percentage points, and after eight weeks 1.6 percentage points (Figure 5). For heartwood (hMC), a statistically significant difference between scenarios occurred for trees stored two (p = 0.007179) and six (p = 0.000000) weeks.

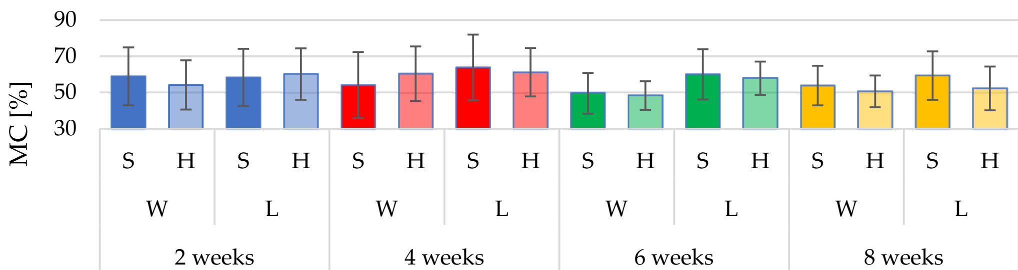

Figure 5. Mean and standard deviation of sapwood MC (sMC) and heartwood MC (hMC) according to storage duration, and storage methods. S—sapwood; H—heartwood; W—scenario W (whole trees); L—scenario L (stemwood).

For tree segment sMC, there were no statistically significant differences between the scenarios. In the second week, higher sMC was observed in the W scenario for the lower and middle parts of the trees. Otherwise, sMC was lower than in the L scenario (Table 6). In scenario W, there was a statistically significant difference for M segment between fourth and sixth week. In contrast, in scenario L, storage (drying) time had no effect on sMC, and no statistically significant differences were observed.

Table 6. Mean and standard deviation of sapwood moisture content (sMC) according to part of the experiment, storage methods and tree segments.

Storage Duration (Weeks after Cutting Down Trees)	Tree Segment	Scenario W [% ± SD]	Scenario L [% ± SD]	*p*-Value
2	B	59.09 ± 15.51	57.16 ± 18.05	1.000000
	M	62.50 ± 18.54	60.40 ± 11.42	1.000000
	T	52.54 ± 10.71	57.53 ± 17.42	1.000000
4	B	54.76 ± 21.94	62.56 ± 19.22	1.000000
	M	55.79 ± 17.10	68.41 ± 14.67	0.836557
	T	48.80 ± 7.34	58.57 ± 20.86	1.000000
6	B	49.83 ± 9.52	55.92 ± 14.54	1.000000
	M	50.57 ± 12.97	62.71 ± 11.67	0.345416
	T	47.20 ± 11.01	63.05 ± 15.22	1.000000
8	B	54.97 ± 12.66	61.57 ± 12.68	1.000000
	M	51.69 ± 8.51	58.47 ± 12.96	1.000000
	T	55.15 ± 11.76	57.54 ± 15.06	1.000000

Note: B—bottom part of the tree (0.0–5.0 m); M—middle part of the tree (7.5–12.5 m); T—top part of the tree (>15.0 m).

For hMC, statistically significant differences between scenarios were shown after six weeks of storage for the lower (B) and middle (M) segments of the trunk (Table 7). In scenario W, there was a statistically significant difference for B segment between fourth and eighth week, for segment M between fourth and sixth week. In scenario L, there was a statistically significant difference only for B segment between fourth and eighth week.

Table 7. Mean and standard deviation of heartwood moisture content (hMC) according to part of the experiment, storage methods and tree segments.

Storage Duration (Weeks after Cutting Down Trees)	Tree Segment	Scenario W [% ± SD]	Scenario L [% ± SD]	*p*-Value
2	B	57.29 ± 14.96	61.81 ± 14.11	1.000000
	M	52.74 ± 13.01	58.91 ± 14.04	1.000000
	T	47.97 ± 6.71	55.30 ± 17.47	1.000000
4	B	63.69 ± 16.25	67.06 ± 11.98	1.000000
	M	57.30 ± 13.89	54.51 ± 12.62	1.000000
	T	55.66 ± 9.55	57.39 ± 10.82	1.000000
6	B	50.64 ± 7.95	59.72 ± 9.85	0.002108 *
	M	45.81 ± 7.71	55.64 ± 7.15	0.031960 *
	T	53.33 ± 7.09	56.76 ± 10.61	1.000000
8	B	53.33 ± 12.66	52.88 ± 10.12	1.000000
	M	48.87 ± 9.76	51.82 ± 14.50	1.000000
	T	46.40 ± 8.96	51.46 ± 12.40	1.000000

Note: * marked effects are statistically significant at $p < 0.05$; B—bottom part of the tree (0.0–5.0 m); M—middle part of the tree (7.5–12.5 m); T—top part of the tree (>15.0 m).

4. Discussion

The results of this study indicated that, for oak wood, transpiration drying (Scenario W) is a faster drying method than air-drying (Scenario L). In scenario W, a statistically significant difference was observed between trees stored six and eight weeks. However, in the L scenario, storage (drying) time had no significant effect on MC. These results are similar to those of a hardwood case study, where transpiration drying was more efficiency method than air-drying [35,43,44].

During the experiment, 20 days with rainfall were recorded. On some of them the rainfall was very intense, above 20 mm. For the area where the study was carried out, the sum of rainfall in the months of July and August 2017 was 224 mm, while in 2018, for example, it was a total of 91 mm (data come from the meteorological station located at the Murowana Goślina Forest Experimental Station). In the period of the most intense rainfall, between the 14th and 28th days of storage, air humidity was on average several percentage points higher than at the beginning and end of the experiment. At high air humidity the dynamics of wood drying decrease, or the opposite phenomenon occurs, namely, an increase in MC (rewetting). This is a known phenomenon and a natural characteristic of wood; rewetting usually occurs in autumn and winter and during very heavy rainfall [22,45–47]. Similarly, transpiration intensity decreases when humidity is high [34]. In our case study, the MC of stems after four weeks of storage was higher than the MC of stems stored two weeks, both W and L scenarios. The iMC of stems stored four weeks was not significantly different from the iMC of stems stored two or six weeks. Thus, MC on the day of measurement should not be affected. Samples for MC measurements were taken from different trees only at the end of each storage period (after two, four, six or eight weeks). For stems stored four, six and eight weeks, there were no additional measurements, and so we do not have accurate knowledge of MC fluctuations. The effect of rainfall on drying is well known; the experiment analyzed here shows MC changes under specific conditions. Despite heavy rainfall and very high humidity, the MC of the stored stems gradually decreased, and transpiration drying was more efficient than air-drying.

In general, transpiration drying is a good solution for preparing biomass from deciduous tree species [25,33,44,48,49]. However, in the case of Scots pine, drying by transpiration is less effective than other methods [24]. Transpiration drying is based on natural physiological processes; most often, transpiration occurs undisturbed for several days after the day on which the tree was cut [34]. This is because trees use water stored in the trunk tissues and/or xylem to minimize imbalances in water supply. The xylem will lose water conductivity after the leaves wither due to severe cavitation and embolism [50]. For example, an MC of approximately 41% is the critical point of water conductivity failure and death for poplar [34].

Leaf wilting is therefore a signal that xylem MC has decreased significantly. During the experiment, signs of leaf wilting were observed between second and fourth week of storage. More specifically, after two weeks there were no obvious signs of turgor loss on all trees. The leaves had no discoloration. After four weeks, signs of wilting and discoloration were clearly visible. After six weeks, the leaves were completely wilted and discolored. Water loss can be correlated with the weight of the leaf samples. On the day the trees were cut, the average leaf sample weighed 29.39 g. After two weeks, the sample weight was about 22% less. Between the second and fourth weeks, sample weight decreased by another 43%, and between the fourth and sixth weeks of drying by about 7%. Thus, the largest statistically significant decrease in mass was shown between leaf samples collected in second and fourth weeks after tree felling. In scenario W, a statistically significant difference in MC was found between wood samples collected after second and sixth weeks of storage. However, comparing the MC of sapwood showed a statistically significant difference only between the samples collected in the second and fourth week.

The sapwood is the so-called "active" part of the stem cross-section, where water flow is not restricted by the natural barriers inherent in heartwood. For this reason, the faster decrease in MC of sapwood compared with heartwood is understandable. However, the MC of heartwood also gradually decreases during drying. Unlike in other species, the MC of oak heartwood is high, similar to the MC of sapwood [37,51].

Area of sapwood significantly affects transpiration drying efficiency [52]. Oak is a tree in which the sapwood is very narrow, its width not exceeding a few centimeters, thus transpiration drying will therefore not be as effective as in other species with a higher proportion of sapwood. In turn, [53] conclude that tree species with thick bark (such as oak) dry slower than those with thin, easily water-permeable bark. Oak dried more slowly than coniferous and other deciduous species. MC loss through bark is also pointed out by [34], who notes that the leaf transpiration, including stomatal and/or residual transpiration of canopy, plays a vital role in decreasing the moisture of the trunk. However, there were no treetops, so the water loss occurred as a result of lenticular transpiration from the bark and as a consequence of the cross-section formed when the canopies were sawn off. Indeed, a more critical factor for the logwood drying process is open wood area, without bark [48,54]. In scenario L, the delimbing process caused some debarking to take place, but water loss via leaves was more effective than the evaporation of moisture via the open wood surface.

A number of experiments on natural drying were conducted in the second half of the 20th century, mainly in the 1980s [17,19,52,55]. However, recently, there has been a resurgence of interest in the topic of natural drying of wood for energy purposes, as biomass is increasingly an alternative to fossil fuels [25,56,57]. Variation in green density and MC are relevant for log transport planning, weight-scaling systems, lumber drying, and dynamic assessment of stiffness [58]. Primary forest biomass is stored in piles along forest or plantation export roads, or it is left on the cut surface. This is a simple pathway for MC reduction that does not require significant financial investment because it is implemented in the harvesting area [27]. Potential costs may result from wood degradation by insects or fungi [9,23,46,59].

The present case study shows changes in MC under specific conditions. The results obtained may differ from those obtained under different weather conditions and with different storage times. However, it is valuable to present them, because oak energy wood is increasingly used on an industrial scale. With this in mind, we have demonstrated differences between traditional air-drying and transpiration drying, which is a good method for preparing biomass for energy purposes.

5. Conclusions

Transpiration drying is a better method for oak stems than air-drying, with a minimum storage time of six weeks in our case study. This coincided with complete wilting of the leaves. Leaf wilting is therefore a signal that xylem MC has decreased significantly. The first signs of wilting and leaf color change occurred earlier, after four weeks of storage. In the W scenario, the MC of sapwood decreased statistically significantly after four weeks of storage. Such a phenomenon was not observed in the L scenario. This indicates that the process of water evaporation from the leaf surface significantly affects the MC pattern in felled oak trees. The MC of heartwood also gradually decreased, especially in scenario W. In the heartwood, natural barriers are formed to stop water flow. In oak, the heartwood has high MC, unlike in most tree species. Explanation of this phenomenon lay outside the scope of this study; however, it indicates how the structure and properties of wood, in addition to storage conditions and methods, influence the efficiency of biomass drying at the harvesting area.

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