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Impact of Different Time Interval Bases on the Accuracy of Meteorological Data Based Drying Models for Oak (*Quercus* L.) Logs Stored in Piles for Energy Purposes

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Abstract

*Natural drying of fuel wood is a feasible option to increase resource efficiency in biomass based energy supply. Meteorological data based drying models are the state-of-the-art to monitor the drying progress. The continuous weighing approach is used to gain data for developing these models. The aim of this study was to investigate the drying performance of oak (*Quercus *L.) logs stored in piles for energy purposes and assess the effect of model time interval base on the accuracy of meteorological data based drying models. The log pile's moisture content dropped from initial 38.9% on February 1, 2013 to 24.8% on October 21, 2013, resulting in a total reduction of 14.1%. At the end, moisture content was distributed evenly within the logs and total dry matter losses were low (2.4%). From load and meteorological data, models were developed including 10-minute, hourly, daily and monthly time interval bases. Model performance was validated by comparing the model estimates to the basic observation. Models proved to be very accurate in estimating moisture content change. Compared to the observation, the hourly time interval based model was the most accurate option (mean deviation of 0.10 ±0.13%), while the least accurate option (10-min interval; 1.49 ±1.29%) was still reasonably accurate. Daily and monthly time interval based models are most suitable for use in the forest industry, as they are accurate, while requiring less extensive and detailed input data than models based on hourly or 10-minute time interval.*

Keywords: meteorological models, drying modeling, fuel wood, natural drying, log wood, woody biomass

1. Introduction

Wood is a major source of renewable energy in the European Union. According to Verkerk et al. (2011), about 380 million m^3 of round wood and 100 million m^3 of fuel wood are harvested per year and the demand is expected to increase between 10% and 35% by 2030. Under current conditions, 744 million m^3 per year could be harvested economically, which is about 58% of the total potential. To realize more of the potential, efficiency in fuel wood supply has to increase (Kamimura et al. 2012). Moisture content is a key parameter in fuel wood supply, as it strongly influences the calorific value and transportation economics. Decrease of moisture content increases the calorific value of the material. In addition, it decreases the amount of water transported per truckload of fuel wood, which is beneficial in terms of payload and shipping volume optimization (Stokes et al. 1987 and 1993, Kaltschmitt et al. 2001, Kofman and Kent 2009, Erber et al. 2016). Natural drying is an efficient and low-cost method to reduce the moisture content of fuel wood (Erber et al. 2012 and 2016). Moisture content of whole trees and logwood is likely to decrease by 20% to 30% during one drying season (Nurmi 1995, Suadicani and Gamborg 1999, Gigler et al. 2000, Nurmi and Hillebrand 2007, Röser et al. 2010, Erber et al. 2012, 2014 and 2016, Raitila et al. 2015). Spring through autumn is the ideal period for drying fuel wood in a stack (Nurmi 1995 and 1999, Höldrich et al. 2006, Nurmi and Hillebrand 2007, Petterson and Nordfjell 2007, Erber et al. 2012 and 2016) and the sooner wood is stored in the year, the faster it will dry to a specific point (Kofman and Kent 2009). Logwood is more advantageous than logging residues, as latter are subject to remarkable dry matter losses caused by biological decomposition processes, which leads to a decrease in net calorific value (Routa et al. 2015a). According to Golser et al. (2005), dry matter losses of logwood usually do not exceed 2% within the first year of storage, while Erber et al. (2012, 2014 and 2016) reported dry matter losses of up to 3.7% when drying beech logs. Contrary, dry matter losses of up to 30% per year (Golser et al. 2005, Routa et al. 2015 a) are reported for logging residues. A further advantage of logs is that they are easier to manipulate during stacking and during chipping. The chip size distribution of logwood chips is more uniform (Nati et al. 2014), which is beneficial in handling at the plant. Neither large shares of oversize particles, which are prone to arching or bridging (Jensen et al. 2004), nor fines, which represent a health issue during storage, are produced.

Oak fuelwood is especially valued in many regions in Europe. Throughout history, oaks have been a source of building material and feedstock for manifold uses (Hogan 2012). In Europe, pedunculate oak (*Quercus robur* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.) are the two most common and valuable species, covering about 49,000 and 38,000 km^2, respectively, in the European Union. In addition, downy oak (*Quercus pubescens* Willd.) covers 25,000 km^2 (Hemery 2008). In Austria, oak species are common only in the eastern part, where a dry climate is predominant. They represent 2.4% (27.4 million m^3) of the stocking volume. The largest shares of oak can be found in the eastern provinces of Lower Austria (4.3% of the province's stocking volume), Burgenland (19.4% of the province's stocking volume) and Vienna (37.7% of the province's stocking volume) (BFW 2016).

Drying of fuel wood has been an intensively studied topic during the last five years. A relatively new approach, continuous weighing, has been employed in a series of drying experiments. The basic principle of this approach is to stack biomass e.g. logs, logging residues, etc. into a metal frame, similar to structures used to hold the load on timber trucks. These frames are placed on load cells. Consequently, the drying progress of the biomass can be followed continuously, assuming that any change in the load weight is due to changes in moisture content. This approach was employed in smaller scale by Gigler et al. (2000) and in larger scale by Kofman and Kent (2009), Erber et al. (2012, 2014 and 2016), Raitila et al. (2015) and Routa et al. (2015a, 2015b). Studied tree species and material types covered spruce (logs and logging residues), pine (logs), birch (logs) and beech (logs).

Natural drying is a process governed by meteorological parameters (Kröll 1978). Accordingly, these are commonly used for modeling the drying progress of fuel wood. Explaining variables usually include precipitation, air temperature, relative air humidity, solar radiation, wind speed or evapotranspiration potential, as well as storage design related parameters like storage duration, use of cover, tree species, mean diameter and volume or diffusion coefficients (Stokes et al. 1987, Gigler et al. 2000, Erber et al. 2012, 2014 and 2016, Raitila et al. 2015, Routa et al. 2015a and 2015b). In case of the continuous weighing, weight change and thus moisture content change is related to one or more of these variables.

Continuous weighing allows gaining high resolution data during the drying progress. As a consequence, models based on raw data require high resolution input meteorological data if they are to be used for estimating a certain pile's moisture content change over a given period of time. Data availability in general and its resolution in particular can be a problem. If an entrepreneur needs to track the moisture content of a large number of piles, he will not be prepared to install a meteorological station near each pile. Therefore, data from state-run stations or interpolated grid data have to be used. Data on daily means or even on monthly level is much easier to access than data on hourly level or, as in the case of the studies by Erber et al. (2012, 2014 and 2016) on a basic 10-minute interval. For this reason, models covering longer time intervals (daily, monthly) are more attractive and convenient for use in the forest industry. Consequently, it needs to be determined if these models are accurate enough. Data from continuous weighing experiments offers the opportunity to answer this question. Accordingly, the objectives of the present study were, firstly, to develop meteorological data based drying models for estimating the moisture content change of oak logwood piles for different time interval bases and, secondly, to determine the impact of different time interval bases on the accuracy of the result.

2. Materials and methods

The storage site was located at Pilgersdorf (province of Burgenland in eastern Austria, 47.4° latitude and 16.3° longitude, 371 m above the Adriatic). The grassy storage site was slightly sloping to the east (~5%), and skirted by a tree line (about 20 m from the pile) in the south, while open in all other directions. In this region, the mean annual precipitation is 749 mm, while the mean annual temperature is 8.4 °C (ZAMG 2014).

A metal frame of 600 kg, similar to those used on timber trucks, was used to stack the logs for the study. Each frame was 2.5 m wide and high, 2.6 to 2.7 m long and built on four load cells (Type HBM 150 kN, Hottinger Baldwin, Germany). Under each of the four frame edges, a load cell was based and the load pressure was distributed evenly by metal plates (30x30 cm) put under the load cells and on top of square edged wooden beams. Ten meters to the west of the frame, a mobile, solar powered meteorological station was set up. All measuring components were installed at a height of 1.5 m to 3.0 m above the ground. Averages of relative air humidity (*RH*, %), air temperature (*TC*, ±0.4 °C), wind speed (*WS*, ±0.3 m s^{-1}), wind direction (*WD*, ±3°), precipitation (P_{Rain}, mm, resolution 0.1 mm h^{-1}), solar radiation (*RA*, W m^{-2}; light spectrum waveband 300 nm to 1100 nm, ±5%) were recorded by a data logger (CR 3000, Campbell Scientific, Great Britain) at a ten minute interval. Total pile mass (±0.05%) was recorded at the same interval from the load cell data. After an hour, data was transferred to a server via GSM network. Temperature data was converted to Kelvin (*TK*) as otherwise contradictory effects could have occurred around 0 °C when determining modeling coefficients.

Oak was harvested in January 2013 and the frame was stacked with oak logs on January 17, 2013. All of the logs (n=129) were measured in length (average of 3.94 ±0.23 m) and diameter (15.8 ±3.8 cm) Average log volume was 0.04 ±0.03 m^3. Total pile volume was 10.5 m^3, while total pile mass was 9772.6 kg. For laboratory analysis, 35 randomly selected logs were sampled by cutting four cm thick sample segments 20 cm from the thicker end of the log. Sample segments were weighed immediately at the storage site and sealed into paper bags for transport. Analysis of initial (39.5 ±3.9%) and final moisture content was carried out in accordance with the European standard EN 14774-2. Additionally, initial bone dry density (658.9 ±50.1 kg m^{-3}) was assessed. All moisture content values were reported on wet weight basis.

In October 2013, the frame was unloaded and logs were sampled again. This time two four cm thick sample segments were taken per log (n=24). Sample segments were located 50 cm from the upper and lower end of the log, respectively. The pile was chipped immediately and ten samples of about one kg chips each were collected for laboratory analysis. Again, both sample segments and chip samples were immediately weighed at the storage site and sealed into paper bags for transport. Laboratory analysis was carried out similarly to the procedure at the beginning. Afterwards, initial and final bone dry densities were compared to estimate dry matter loss. Additionally, in-log moisture content distribution was sampled in detail at the end of the experiment. From eight logs, four cm thick sample segments were cut at 25%, 50% and 75% of the total log length. These logs were selected randomly and originated from all sections of the pile, except the undermost and topmost section.

Due to technical issues related to the meteorological station, the study period started 13 days after stacking. Nevertheless, pile weight and moisture content were monitored from the stacking on. Therefore, starting weight and moisture content could be determined on February 1, 2013. From this point on, the pile was monitored for 262 days till October 21, 2013. During this period, the drying progress could be tracked via the pile weight change. However, the reason for this change cannot be determined that easily during winter season, as it can either result from drying, rewetting or snow cover buildup. Snowfall amount was estimated under assumption that a rise in pile weight at an air temperature of around 0 °C (273.1 K) is the result of snow deposition on the pile. Accordingly, the rise in weight was divided by the pile surface area. This weight was then converted to rainfall equivalents (P_{Snow}; one mm precipitation per one kg m^{-2}). Nevertheless, both due to snow drift by wind and the inability to accurately capture snow melting in spring, snow remains a source of inaccuracy in load monitoring. Yet it is not unreasonable to assume that the effect of snow related load weight change is also present in spring.

Analysis followed an approach successfully employed in former studies (Erber et al. 2012, 2014 and 2016, Routa et al. 2015a and 2015b). Initially, weight change between measurement points was calculated. Next, weight change was converted to moisture content change (*MCA*), starting from the baseline moisture content assessed in laboratory. After calculation on the basic 10-minute interval level, data was aggregated on hourly, daily and monthly level. Means (*MC*, *WS*, *TK*, *RA* and *RH*) and sums (*MCA*, sum of P_{Rain} and P_{Snow} (*P*)) were calculated. On 10-minute, hourly and daily level, the season factor (*SE*; defined by winter and summer solstice, spring and fall equinox) was included into the explaining variables dataset. Lastly, the days since storage start (*DY*) were included as possible explaining variables in the monthly level dataset.

After that, multiple linear regression models, which estimate moisture content change (%) on the respective time interval level, were developed. Their common principle is that moisture content change is a function (1) of meteorological parameters and season (1) (10-minute, hourly, daily time interval level) or storage duration (2) (monthly time interval level). Variance analysis and variable correlation checks were performed. Accuracy of the models was assessed by their mean deviation and respective standard deviance from the observed basic 10-minute time interval level curve. For this purpose, estimates were calculated on the respective time interval basis. To enable comparison of the different time interval base estimates to the 10 minute observation level, for hourly, daily and monthly level, missing values between estimates were approximated linearly.

$$MCA = Intercept + WS + TK + RH + RA + P + SE \quad (1)$$

$$MCA = Intercept + WS + TK + RH + RA + P + DY \quad (2)$$

Where:

MCA Moisture content alteration per time interval, %
WS Mean wind speed per time interval, m s^{-1}
TK Mean air temperature per time interval, K
RH Mean relative air humidity per time interval, %
RA Mean solar radiation per time interval, W m^{-2}
P Mean precipitation per time interval, mm
SE Season
DY Days since storage start, n

To prevent any unfavorable results due to use of the models in an improper environment, the valid range of the models was limited by the 5% and 95% quantile of the explaining variables. Respective limits are presented in Table 1. Generally, the models shall only be used for oak logs with bark with a length between 3.50 m and 4.50 m and diameters of 10 cm to 30 cm.

Table 1 Valid range of the models is defined by the 5% and 95% quantile of the explaining meteorological parameters

Model basis	*WS*, m s^{-1}	*TC*, °C	*RH*, %	*RA*, W m^{-2}	*P*, mm
10 minutes	0.0–3.7	–2.6–26.4	42.7–99.8	0.0–0.8	0.0–0.1
Hourly	0.0–3.5	–2.6–26.4	42.8–99.8	0.0–0.7	0.0–0.5
Daily	0.3–2.9	–2.1–23.6	60.2–94.2	36.5–319.6	0.0–13.3
Monthly	0.7–1.5	0.4–19.9	68.5–84.9	78.0–257.5	7.0–145.3

WS = wind speed; *TC* = air temperature; *RH* = relative air humidity
RA = solar radiation; *P* = precipitation

3. Results

Daily mean wind speed was 1.0 ± 0.9 m s^{-1}, while daily mean temperature and relative air humidity were 11.6 °C (284.7 ± 7.8 K) and 77.7 ± 10.9%, respectively. Solar radiation was 168.0 ± 92.0 W m^{-2} on average. A total sum of 530.9 mm of rainfall was recorded. During the observation period, the largest shares of rainfall were observed in May (135.0 mm), September (86.3 mm) and July (79.3 mm). The estimated amount of snowfall totaled 180.0 mm in rainfall equivalents.

The oak log pile's moisture content decreased from 38.9% on February 1, 2013 to 24.8% on October 21, 2013, resulting in a total reduction of 14.1%. From March to August the moisture content dropped steadily. Drying then slowed down considerably, and finally remained relatively stable until the end of the observation period. In March, June and July, the highest monthly drying rates (4.1–4.8%) were observed, while the pile's moisture content increased during rainy May (1.2%) and humid September (1.8%). The lowest moisture content (24.1%) on daily basis was observed on September 8, while the highest moisture content (40.0%) on daily basis was recorded on February 25, 2013. At the end, the mean moisture content of the sample segments (*n*=24) was 24.1 ± 4.1%, while the mean moisture content of the chip samples (*n*=10) was 25.2 ± 1.1%. Final pile weight was 7932.1 kg. No dry matter losses were observed, if only the mean of all logs sampled in the beginning was compared to the mean of all logs sampled in the end. If comparison was only limited to logs that were sampled both in the beginning and at the end, a mean dry matter loss of 2.4% was observed. The initial intention had been to sample the same logs in the beginning and at the end, but even though logs had been provided with an ID, not all could be recognized again, as a share of the ID tags came off from the logs. For this reason, a number of substitute logs were selected.

Reasonably fitting models could be developed for all time intervals (Tables 3–6). Model statistics are displayed in Table 2 and models are used together with Eq. 1 and 2. *SE* was only significant on 10 minute and hourly level, while *DY* was not significant at all. *RA* and *P* were significant in all models. It showed that

Table 2 Overview of developed oak log drying models

Time interval	Std. error	R^2 adj.	*p*-value	Mean deviation from the observation
10-minute	0.01	0.54	$<2.2\text{x}10^{-16}$	1.49±1.29%
Hourly	0.05	0.58	$<2.2\text{x}10^{-16}$	0.10±0.13%
Daily	0.25	0.71	$<2.2\text{x}10^{-16}$	0.66±0.51%
Monthly	1.17	0.76	$1.6\text{x}10^{-2}$	0.62±0.49%

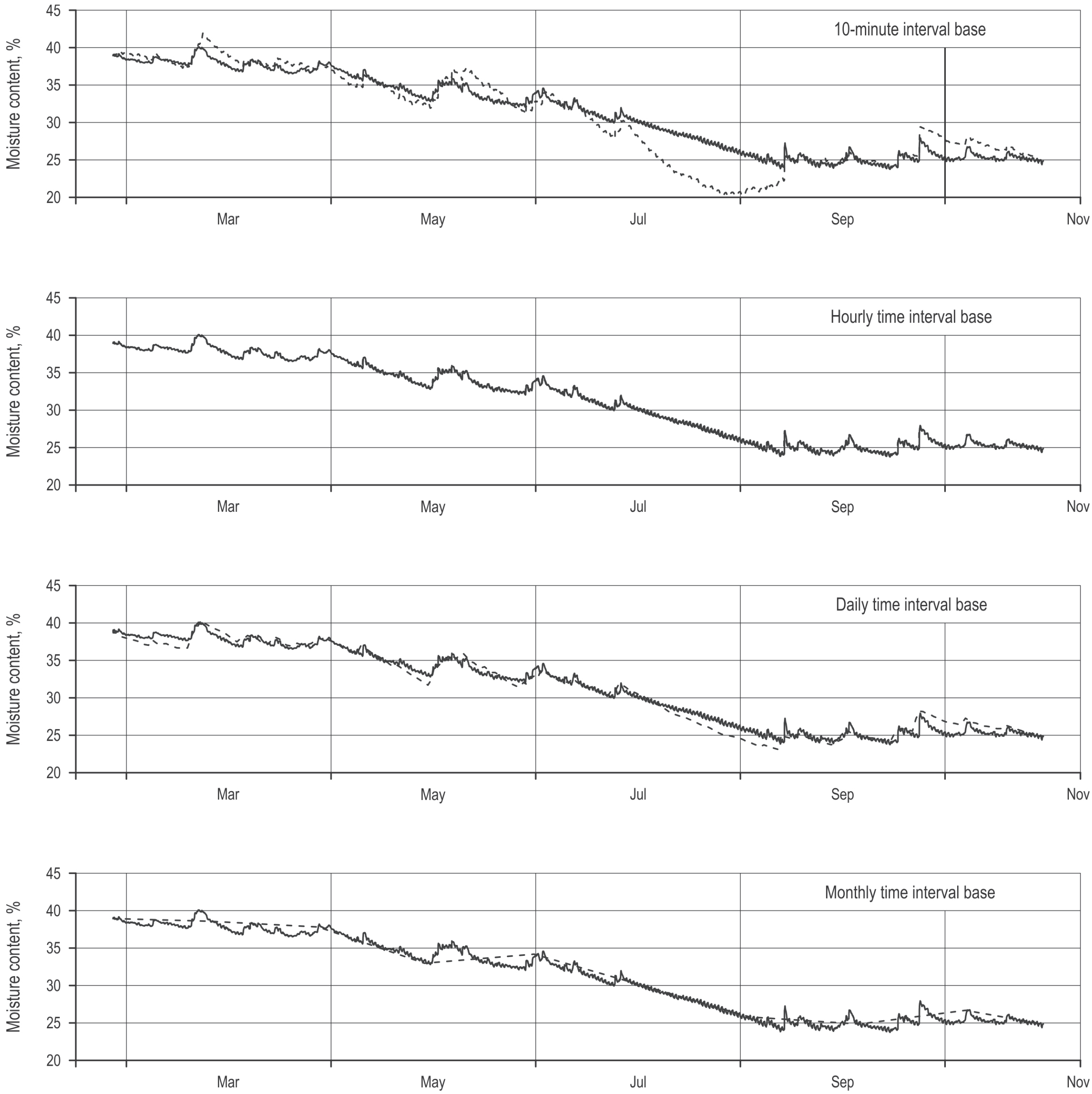

Fig. 1 Observed drying performance (continuous line) and estimated drying performance (dashed line) of the oak log pile during the drying period February to October 2013 for different time interval bases (estimated performance on hourly time interval base was almost perfectly similar to the observation)

deviation of the hourly level estimation from the observation was the lowest (0.10 ± 0.13% in moisture content). Estimates generally did not differ from the observed drying performance to a large degree, except for the 10-minute time interval based estimation. This level also showed the largest single deviation (5.11%) (Fig. 1).

Detailed analysis of in-log moisture content distribution showed that moisture content did not differ significantly between the bottom, middle and top section of the logs. Moisture content did differ significantly (p-value=1.8×10^{-5}) between the logs, but no significant correlation between moisture content and log volume could be observed.

Table 3 Model statistics, parameters estimate, Student's *t*-test and summarized test statistics of 10-minute time interval oak log drying model

Parameter	Estimate	Std. error	*t*-value	*p*-value
Intercept	-4.43×10^{-2}	4.55×10^{-3}	–9.74	$<2.0\times10^{-16}$
WS, m s^{-1}	-5.30×10^{-4}	6.24×10^{-5}	–8.50	$<2.0\times10^{-16}$
TK, K	2.04×10^{-4}	1.52×10^{-5}	13.46	$<2.0\times10^{-16}$
RH, %	-1.39×10^{-4}	5.97×10^{-6}	–23.31	$<2.0\times10^{-16}$
RA, W m^{-2}	-2.48×10^{-2}	4.12×10^{-4}	–60.34	$<2.0\times10^{-16}$
P, mm	9.69×10^{-2}	4.92×10^{-4}	197.01	$<2.0\times10^{-16}$
SE_{Spring}	-4.66×10^{-4}	2.21×10^{-4}	–2.11	3.4×10^{-2}
SE_{Summer}	-6.26×10^{-4}	2.41×10^{-4}	–2.60	9.5×10^{-2}
SE_{Winter}	-1.01×10^{-3}	2.87×10^{-4}	–3.50	4.7×10^{-2}

WS = wind speed; *TK* = air temperature; *RH* = relative air humidity
RA = solar radiation; *P* = precipitation; *SE* = Season

Table 4 Model statistics, parameters estimate, Student's *t*-test and summarized test statistics of hourly time interval oak log drying model

Parameter	Estimate	Std. error	*t*-value	*p*-value
Intercept	-3.83×10^{-1}	3.92×10^{-2}	–9.75	$<2.0\times10^{-16}$
TK, K	1.58×10^{-3}	1.33×10^{-4}	11.90	$<2.0\times10^{-16}$
RH, %	-6.65×10^{-4}	5.21×10^{-5}	–12.77	$<2.0\times10^{-16}$
RA, W m^{-2}	-1.46×10^{-1}	3.98×10^{-3}	–36.63	$<2.0\times10^{-16}$
P, mm	-8.68×10^{-2}	1.04×10^{-3}	83.49	$<2.0\times10^{-16}$
SE_{Summer}	-5.70×10^{-3}	2.21×10^{-3}	–2.58	1.0×10^{-2}

TK = air temperature; *RH* = relative air humidity; *RA* = solar radiation; *P* = precipitation; *SE* = Season

Table 5 Model statistics, parameters estimate, Student's *t*-test and summarized test statistics of daily time interval oak log drying model

Parameter	Estimate	Std. error	*t*-value	*p*-value
WS, m s^{-1}	-8.21×10^{-2}	1.77×10^{-2}	–4.64	5.6×10^{-6}
RA, W m^{-2}	-1.15×10^{-3}	2.69×10^{-4}	–4.26	2.9×10^{-5}
P, mm	7.00×10^{-2}	3.24×10^{-3}	21.63	$<2.0\times10^{-16}$

WS = wind speed; *RA* = solar radiation; *P* = precipitation

Table 6 Model statistics, parameters estimate, Student's *t*-test and summarized test statistics of monthly time interval oak log drying model

Parameter	Estimate	Std. error	*t*-value	*p*-value
Intercept	–134.80	37.84	–3.56	1.6×10^{-2}
TK, K	4.87×10^{-1}	1.39×10^{-1}	3.51	1.7×10^{-2}
RA, W m^{-2}	-4.95×10^{-2}	1.34×10^{-2}	–3.71	1.4×10^{-2}
P, mm	3.62×10^{-2}	9.58×10^{-3}	3.78	1.3×10^{-2}

TK = air temperature; *RA* = solar radiation; *P* = precipitation

4. Discussion

Natural oak log drying has never before been modeled depending on either meteorological or any other data. The developed models offer the opportunity to estimate the logs drying performance on different time interval bases, ranging from a 10-minute or hourly time interval suitable for scientific purposes to daily and monthly time intervals fit to e.g. entrepreneur's requirements.

The experimental setup did not differ from the setup and procedure in Erber et al. (2012, 2014 and 2016) to a large degree, which is of great benefit in comparing the results. Unique to this experiment were the tree species and partly the modeling time intervals (10 minutes, hourly and monthly interval). Other studies conducted with the same experimental setup confirm the usefulness of the continuous weighing approach (Raitila et al. 2015, Routa et al. 2015b).

Moisture contents established from the samples in the end proved to be similar to the moisture content estimated from the continuous weighing. It showed that dry matter loss sampling is a tricky procedure, not only for logging residues (Routa et al. 2015a), but also for logs. If one is not able to compare the same logs, differences between logs and in-log variation can affect the sampling procedure to a certain degree. Thus the established dry matter loss of 2.4% can be considered a reasonable, but nevertheless only rough estimation. The result at least matches dry matter loss rates for log wood found in literature (2% per year; Golser et al. 2005).

The total moisture content drop of 14.1% during one drying season indicates the need for a second drying season if one wants to reduce the moisture content to 20% or below. Further, if the starting moisture content was higher than the observed 39.5%, a second drying cycle would be inevitable to reach moisture contents below 30%. Golser et al. (2005) conclude that tree species with thick bark (like oak) dry slower than those with easily water permeable, thin bark. Oak dried slower than coniferous and other deciduous species. Another explanation could be an effect observed by McMinn (1986). While diffuse-porous and coniferous species moisture content could be substantially reduced by leaf-seasoning (drying trees in foliage), this was not the case with ring-porous species like oak. The author attributed this effect to the fact that ring-porous species have a proportionally smaller area of active conductive tissue. This means that the proportion of sapwood to heartwood is smaller than in diffuse-porous and coniferous species and thus less moisture can be removed within the same period. Other authors came to the same conclusion (Johnson and Zingg 1969, Clark and Phillips 1972, Simpson 1991).

The longer the time interval length, the fewer variables constituted the explaining variable dataset. While during short time interval modeling (10 minutes, hourly) almost all variables in the dataset were of significant impact, the number of explaining variables reduced to three for the long term interval models (daily, monthly). It can be assumed that during longer intervals the more slowly altering variables gain importance, while the impact of those responsible for short time change declines. Contrary to other studies (Filbakk et al. 2011), no impact of the storage duration (*DY*) could be observed. This may indicate that oak has not yet reached the low moisture content level, where drying slows down due to stronger bonds between wood and water. This effect was observed in Erber et al. (2016), where beech dried the slower, the lower the moisture content was on the day before. Among others, Klepac et al. (2008) report significant effects of season on the drying of loblolly pine (*Pinus taeda* L.). In summer, trees dried about 50% faster than in autumn and winter. In the present study, seasonal effects were discovered for 10-minute and hourly time intervals but not for daily interval models. Here the seasonal effects may cover some of the otherwise unexplained variation in 10-minute and hourly interval data. In daily data, the variation is probably lost due to averaging effects.

Datasets were checked for correlations between variables and, especially in short intervals datasets, some were discovered. As their consideration did not improve the models performance and would unnecessarily inflate the models beyond usability, they were excluded from the models. In general, the employed datasets are in line with other studies (Stokes et al. 1987, Filbakk et al. 2011, Erber et al. 2016).

Estimation proved to be the most accurate on hourly level, but an extensive and detailed set of basic data is still required for its use. However, daily and monthly time interval based models were almost as accurate as the hourly time interval based model, but they require a smaller number of input parameters and less detailed data. Accordingly, it can be concluded that these models are suitable for use in daily business in the forest industry, while the use of hourly time interval base models is limited to scientific purposes.

In-log moisture content distribution at the end of the drying period matches research results of Neußer et al. (1977). A slight decline in mean moisture content from bottom to top was observed. This effect is likely to correspond to the respective decrease in log diameter. Naturally, logs at the top of a pile are more exposed to wind, rain and solar radiation. To avoid edge effects, sample piles were selected from neither the undermost nor the topmost row.

As discovered in previous studies (Erber et al. 2012, 2014 and 2016), the major weakness of the actual setup is the inability to assess the behavior of snow cover appropriately. Since the drying period of this experiment touched the snow season to a lesser degree than experiments with a run time of more than one year, this probably did have less effect on the results. To better fit to real life conditions, future studies will also have to deal with multi-species piles and different climate conditions.

5. Conclusions

In the present study, meteorological data based drying models could be developed for oak logs stored in piles. Model time interval bases included 10-minute hourly, daily and monthly intervals. Models proved to be very accurate in estimating moisture content change and in comparison with the observed drying performance, regardless of the time interval base. Daily and monthly time interval level based models are most suitable for use in the forest industry, as they are accurate, while requiring less extensive and detailed input data than models on hourly or 10-minute time interval base. The latter are more suitable for scientific purposes. The present study confirmed that dry matter losses of fuel wood stored as logs may be much lower than those recorded for logging residues and whole trees and that natural drying is an effective method for reducing fuel wood moisture content. However, oak logs shall generally be subject to a drying period of two successive summer seasons to achieve moisture contents of around 20%.

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