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Predicting Moisture Content in a Pine Logwood Pile for Energy Purposes

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Determining the moisture content of naturally dried fuel stock without frequent measuring is a problem still unsolved. Modelling moisture content based on automatically captured meteorological data could provide a solution. An accurate model would allow the drying period and the point of chipping to be optimised. For the experimental study, a metal frame supported by load sensors and loaded with 17 tons of logwood was set up next to a meteorological station. A multiple linear regression model was used to link meteorological and load data to provide a formula for determining the moisture content. The pile dried for a period of 14 months (average temperature of 7.3 °C, a humidity of 81%, and 777 mm of rainfall). The overall moisture content dropped from 50.1% to 32.2%. The regression model, which based on daily means and sums of meteorological parameters, provided a mean deviance from the observed curve of –0.51% ± 0.71% within the period of investigation. Relative humidity was found to be most important parameter in drying. Increased moisture content resulting from rainfall greater than 30 mm per day reverted back to pre-rainfall values within two to three days, if no other rainfall events followed. Covering the pile would have a positive effect on the drying performance. In terms of economic benefit it could be shown that natural drying is beneficial. Overall this study shows that meteorological data used in site specific drying models can adequately predict the moisture content of naturally dried logwood.

Keywords moisture content, natural wind drying of fuel wood, modelling, log pile
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1 Introduction

The quality of biomass fuel stock can be measured in several ways. One common method is measuring the moisture content. The moisture content influences the calorific value, which increases with decreasing moisture content (Hartmann and Kaltschmitt 2001). Drying in piles can help to decrease the moisture content significantly within a short period. Depending on the conditions during the drying period, whole trees and logwood are likely to lose up to 20%–30% in moisture content within 5 to 6 months (Nurmi 1995, Suadicani and Gamborg 1999, Gigler et al. 2000, Nurmi and Hillebrand 2007, Röser et al. 2010). If harvesting residues are stored, compacted or un-compacted, similar drying rates can be observed (Jirjis 1995, Nurmi 1999, Nordfjell and Liss 2000, Nurmi and Hillebrand 2007, Petterson and Nordfjell 2007). In contrast, Nurmi (1999) demonstrated that storing harvesting residues as wood chips increases the moisture content within the same period. Drying as logwood is beneficial, due to low dry matter losses of 2% a year for logwood of Norway spruce [*Picea abies* (L.) Karst.] and Scots pine [*Pinus sylvestris* (L.)] (Golser et al. 2005). The seasons of spring through autumn provide the ideal conditions for drying in a windrow (Nurmi 1995, Nurmi 1999, Höldrich et al. 2006, Nurmi and Hillebrand 2007, Petterson and Nordfjell 2007). The sooner wood is stored in the year, the faster it will dry to a specific point (Kofman and Kent 2009). If the windrows are covered, the drying period can be extended one more year, for example if harvesting took place in late summer, to gain further drying. (Höldrich et al. 2006, Nurmi and Hillebrand 2007, Petterson and Nordfjell 2007). The effect of covering depends on climate conditions. In countries such as Ireland and Finland, covering has a strong effect, due to humid periods in autumn and winter (Nurmi and Hillebrand 2007, Petterson and Nordfjell 2007, Röser et al. 2010). In contrast, covering of piles shows no effect under the dry conditions of Italy (Röser et al. 2010). Furthermore, covering a pile in the woods is more important than in an open area, due to less access to wind (Kofman and Kent 2009). The achievable effect of covering is considered to range from a 3%–6% reduction in moisture content, compared to uncovered piles (Jirjis 1995, Nurmi and Hillebrand 2007). Elevated and open-area storage is beneficial to the drying progress (Kofman and Kent 2009).

Drying in windrows by convection is a process governed by temperature, relative humidity, wind speed and rainfall (Kröll 1978). Kofman and Kent (2009) consider wind access and sun to have the greatest impact on drying. Any kind of modelling has to consider these parameters. A single stem can be regarded as a “non-shrinking, infinite long cylinder of homogenous wood material surrounded by bark” (Gigler et al. 2000). Radial water transport thus depends on the different diffusivities of wood and bark (Gigler et al. 2000). Considering whole windrows, modelling can be based on time, climate conditions, species and other species related parameters, like crown size and foliage (Filbakk et al. 2011). A similar model was developed by Ottmar and Sandberg (1972) for the prediction of fire danger in forests depended on the daily precipitation and its duration and the minimum and maximum temperature and relative humidity. Kofman and Kent (2009) carried out an experiment with logs of energy wood and pulp wood in metal frames based on load sensors. From different starting dates, it was observed when the piles would reach 30% in moisture content. Their dependent variable was the time of storage, the independent variable were starting date and storage time.

A major unsolved problem is how to determine the moisture content within a pile without measuring it frequently. Modelling the change of moisture content of a pile depending on automatically measureable input variables could help to optimize drying periods and determine the time of chipping.

The objective of the study was to develop a model for predicting the change of moisture content by simulating natural drying and change of moisture content of a logwood pile. A major goal was to observe the effects of heavy rainfall and simulate the effects of coverage of pile on drying performance. Further an economic analysis was carried out.

2 Material and Methods

2.1 Experimental Design

The natural drying experiment took place from 2009 to 2011 (16th December 2009 to 10th February 2011). The study was carried out at Hartberg in Styria/Austria (47°17´N, 15°58´E; 350 m above the Adriatic). The Scots pine [*Pinus sylvestris* (L.)] logs were harvested nearby in December 2009. Before the experiment was conducted, all logs were measured in diameter and length. Then 15 cm slices were taken from the thicker end of sample logs for laboratory analysis. Logs were provided with identification (ID), to be able to take sample slices of the same logs in the end (Table 1). All moisture content values are reported at wet basis (MCwb).

The logs were piled up at a storage area in a metal frame, similar to those used on timber trucks. The frame was 2.5 m in width and height and 3 m in length. It was based on load sensors (Type HBM, 150 kN) which were placed on metal plates (50 cm × 50 cm) under the four edges of metal frame. The first row of logs was located 30 cm above ground level. The ground was bare soil and gravel. The area around the ground was open to the east and the north and blocked by firewood piles in logwood pile height in the west and the south within a distance of 2 m. A meteorological station was set up 5 m to the east of the frame. All measuring components were installed at a height of 1.5 m to 2.5 m. Relative humidity (%), temperature (°C), wind speed (m s^{-1}) and rainfall (mm) were recorded. A data logger (Campell CR3000) collected the data from both the meteorological station and the load sensors. Every ten minutes, meteorological data and total pile mass were recorded. Recording covered averages, maxima and standard deviances of wind speed (WS, ±0.3 m s^{-1}) and wind direction (WD, ±3°), averages of temperature (T, ±0.4 °C) and relative humidity (RH, ±2%) as well as sums of total pile mass (PM, ±0.05%) and precipitation (P, resolution 0.1 mm h^{-1}). All compiled data was transferred to the University of Natural Resources and Life Sciences' server once daily. At the end of the experiment, sample slices were taken again.

2.2 Statistical Analysis

For statistical analysis, multiple linear regression models were chosen. Before starting, data had to be prepared for analyses. Non-liquid precipitation was transformed to equivalents of liquid precipitation. To achieve that, each rise of pile mass during a period of temperature below 0 °C was considered to be caused by non-liquid precipitation. The reason for this transformation was that the measuring pitcher used included no heating unit. The change in mass was transformed into mm m^{-2} rainfall. It was assumed, that if a snow-covered pile was chipped, the snow would melt in the chipper and wet the chips. Hence, non-liquid precipitation was included in modelling.

Three model assumptions were made. First, it is possible to predict the change of the moisture content depending on simply measureable input components like wind speed (WS), temperature (T), relative humidity (RH) and precipitation (P). Second, it is possible to assess the effect of heavy

Table 1. Parameters of logs in the experiment.

Parameter	
Total number of logs in the experiment	208
Average length	4.72 m ± 0.50 m
Average diameter	15.2 cm ± 5.3 cm
Number of sample logs	42
Initial moisture content	50.1% ± 4.2%
Initial oven dry density	509 kg m^{-3} ± 45kg m^{-3}
Initial wet density	1028 kg m^{-3} ± 163 kg m^{-3}
Initial total load	17630 kg
Initial total volume (solid volume of wood and bark)	19.5 m^3

rainfall on the drying performance. Third, natural drying provides satisfying drying rates, justifying longer storage time, both in terms of moisture content and economic value.

To test the first assumption, four basic approaches were chosen. All model variates were tested based on means or sums for each hour and day. Further, variates were tested for both including and excluding non-liquid precipitation. This data was considered the raw experiment data.

The dependent variable in all model variates was the change of moisture content within the pile of round wood logs, based on changes in pile mass. The independent variables were precipitation, temperature, drying potential of the relative humidity and wind speed. Drying potential of the relative humidity (DP) was calculated by subtracting the measured relative humidity from 100% of relative humidity. Data collection on the moisture content started from the initial moisture content assessed in laboratory in the beginning.

First, a model based on the raw data of the experiment was constructed (Variates A1–A4). In the second model, data was separated into parts of increase and decrease in the pile mass. Therefore, two equations, one for drying and one for rewetting, were to be found. Simulating the decrease and increase of weight separately should provide the change in moisture content, if increase and decrease were summed up for each period (Variates B1–B4). The third model was based on both the data of the first and the second models, only covering the variates including liquid and non-liquid precipitation. A moving average of the input variables was calculated, to flatten outliers. The moving average was limited to a maximum of twelve hours in simulating on an hourly basis and to a maximum of seven days, when simulating on daily base (Variates C1–C4). Contrary to the three others, the fourth model did not work with means (temperature, relative humidity, wind speed) and sums (precipitation) of input. Instead, all variables were input as sums. Normally there should be no difference in output, compared to the first variate (Variates D1–D2). A summary of all variates is given in Table 2.

The best fitting model for determining the moisture content of the pile was selected in a multi-level process. All variates of models were calculated with the data prepared according to procedure described in the methods section. The models were compared by their mean deviance of the observed drying curve. The coefficients of determination and the quartiles of deviance were taken in account. Finally a box and whiskers chart was drawn, to illustrate the selection process (Fig. 3).

2.3 Sensitivity Analysis

To test which variable had the strongest impact on drying success, a stepwise regression model was used. First the strength of the relationship between

Table 2. Summary of all tested model variates.

Variate	Input data	Modelling basis
A1	Raw data averages; liquid and non-liquid precipitation sum	Hourly basis
A2	Raw data averages; liquid precipitation sum	Hourly basis
A3	Raw data averages; liquid and non-liquid precipitation sum	Daily basis
A4	Raw data averages; liquid precipitation sum	Daily basis
B1	Data split averages; liquid and non-liquid precipitation sum	Hourly basis
B2	Data split averages; liquid precipitation sum	Hourly basis
B3	Data split averages; liquid and non-liquid precipitation sum	Daily basis
B4	Data split averages; liquid precipitation sum	Daily basis
C1	Moving average of A1; liquid and non-liquid precipitation sum	Hourly basis
C2	Moving average of B1; liquid and non-liquid precipitation sum	Hourly basis
C3	Moving average of A3; liquid and non-liquid precipitation sum	Daily basis
C4	Moving average of B3; liquid and non-liquid precipitation sum	Daily basis
D1	Raw data sums; liquid and non-liquid precipitation sum	Hourly basis
D2	Raw data sums; liquid and non-liquid precipitation sum	Daily basis

the predictable variable and the explaining variable was checked separately. Then the explaining variables were taken from the model step by step, starting with the less explaining variable. The change in the R^2-value showed how much impact every variable had on the predictable variable.

2.4 Simulation of Covering the Pile

In addition, a simulation of the effect of covering the pile was carried out for the selected model, setting the precipitation to zero, but maintaining the effect of rewetting by relative humidity. Taking the effect water seeping through the cover in account, a second simulation should provide estimation on what amount of water has to seep through to achieve the reference values of 3% to 6% decreases in moisture content because of the cover (Jirjis 1995, Nurmi and Hillebrand 2007).

2.5 Heavy Rainfall

To assess the effect of heavy rainfall, the three heaviest single events of rainfall (per day) in the observation period were selected and analysed. The most important aspects were the time necessary to regain the moisture content before the event and how following events of rainfall affected the drying process. The goal was to give a rough estimation on that.

2.6 Drying Performance within the Pile and the Log

A further point of interest was how the drying performance varies with pile height. At the end of the experiment 15 cm thick slices were cut out of three logs (one from each the upper, middle and lower pile third) with a distance of 33 cm between the slices. The cutting started from both ends of the log and the last slice was located in the middle between adjacent slices. The slices were analysed on their moisture content. Therefore, a distribution chart of moisture content within the log could be drawn.

Table 3. Prices (Pr) for fuel wood delivered to "BioEnergie Stainach GmbH" based on moisture content and given in Euros per absolutely dry ton (ton abd) (Mr. Stadler, Bioenergie Stainach Gmbh, personal communication 09.05.2011).

Moisture content	Price delivered to plant
0%–34%	96.00 € ton abd^{-1}
35%–49%	92.00 € ton abd^{-1}
50%–55%	88.00 € ton abd^{-1}

2.7 Economic Benefit

To assess the economic benefit of drying, a cost-benefit-analysis was carried out for the period of April 2010 to September 2010. Calculation basis were prices for fuel wood (Pr) delivered to the plant of the "BioEnergie Stainach GmbH" (May 2011). An overview on that is given in Table 3. Prices are given in ton abd (absolutely dry ton; dry matter (moisture content 0% at wet basis)). Two variates were calculated. The first one included selling the fresh cut logs in April and charging interest (*I*) at an interest rate (*i*) of 2% for the capital (*C*) till September. Therefore Eq. 1 was used. The second variate included drying until September and selling the dried logs then. Further the pre-financing of harvesting was taken in account by using Eq. 1 for charging interest on harvesting costs (*C*) at the same interest rate as in variate one. Local harvesting costs were 20 € m^{-3}, converted to one ton aid (air dry ton; ton of wood at a specific moisture content; for conversion a factor of 1.56 ton aid m^{-3} at a moisture content of 35% (Austrian Energy Agency 2009) was used) resulted in 31.20 € ton aid^{-1}. Results are given for one ton aid, to sustain comparability. The conversion of tons abd to tons air and calculation of the price earned (*Pe*) is presented in Eq. 2.

$$I = \frac{C \times i \times d}{360 \times 100} \tag{1}$$

I = interest (€)
C = capital at the start (€)
i = interest rate (%)
d = days of yielding interest

$$Pe = \frac{(100 - MC)}{100} \times Pr \qquad (2)$$

Pe = price earned for one ton aid (€)
MC = moisture content (%)
Pr = price paid for one ton abd (€)

2.8 Valid Range

The valid range of every model variate for any further use depends on the input data and should be limited by the 5% and 90% quantile. Respective limits for hourly (h) and daily (d) basis are given in Table 4. Limits for temperature (T), relative humidity (RH) and wind speed (WS) are averages, those for precipitation (P) sums. The models can be used for pine logs with lengths from 3.5 m up to 5 m and diameters from 8 cm to 22 cm.

Table 4. Limits for the valid range of the model variates: the 5% and 90% quantile on hourly (h) and daily (d) basis.

Basis	T (°C)	RH (%)	P (mm m^{-2})	WS (m s^{-1})
5% h	–6.87	44.3	0.00	0.02
90% h	20.2	99.9	0.11	1.13
5% d	–5.99	56.1	0.00	0.15
90% d	19.7	97.0	7.50	0.76

3 Results

3.1 Descriptive Data

During the investigation period of 417 days, a mean temperature of 7.37 °C ± 9.68 °C, during the year 2010 a mean of 8.67 °C ± 9.46 °C (long term average: 9.3 °C) was observed. The mean wind speed was 0.46 m s^{-1} ± 0.44 m s^{-1} during the investigation period. The observed maximum wind speed was 8.49 m s^{-1} and the dominating wind direction was from the south. The average relative humidity was 81.14% ± 18.63%. Most of the liquid precipitation fell in the period of May to October, with single events of up to 39 mm a day. In total a sum of 777 mm was observed. Furthermore, an equivalent of 276 mm in non-liquid precipitation, as in snowfall, was calculated (Fig. 1).

The logwood pile dried very slowly in winter, but the drying started to increase in March with a drying rate of 1.9% per month in moisture content. In June and July drying rates of up to 4.5% per month were observed. In August the drying rate fell to 1.0% and remained low until October (0.7%). In November the pile slightly

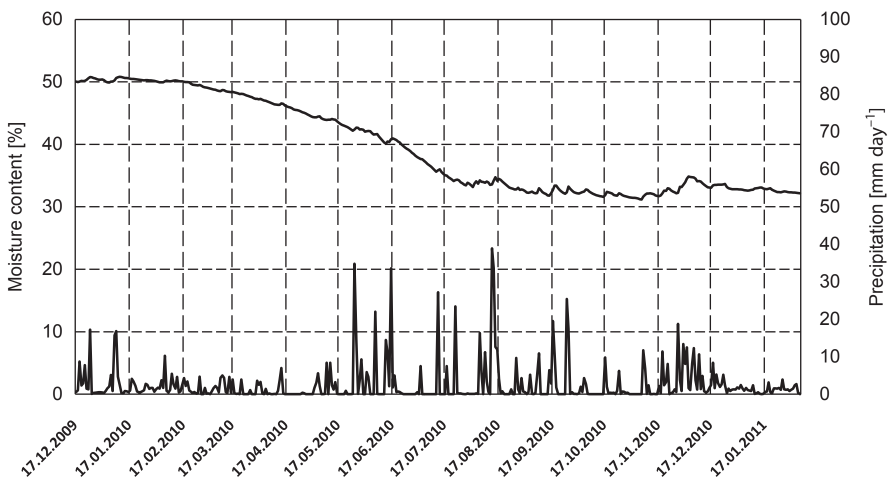

Fig. 1. Drying curve of the pile within the investigation period based on load sensor data and precipitation data from 2009 to 2011.

gained weight (1.6%). At the end of the investigation period the moisture content was 32.2% as assessed by overall weight loss of the pile. The lowest moisture content (31.1%) was recorded on the 07th November 2011 (Fig. 1). In total the moisture content of the pile had decreased 17.9%. The 42 wood slice samples taken for laboratory analyses showed average lower moisture content of 29.5% at the end. A dry matter loss of 5% was recorded within the investigation period. This indicates an average of 0.35% per month.

The distribution of the moisture content within the pile was investigated in detail. It became evident that logs from the upper (moisture content in the end: 34.49% ± 5.72%) and the lower section (22.25% ± 2.87%) dried better than those in the middle (42.66% ± 7.40%). Furthermore, it showed that in the upper and middle logs, the slim parts (18.43%; 23.11%; values on the upper end of the log) showed lower moisture contents than the thicker parts (25.66%; 49.35%.) The log in the lower section dried more or less uniform (19.76%; 15.33%; values of lower and upper end of the log).

3.2 Model Selection

Modelling showed that variates including both liquid and equivalents of non-liquid precipitation worked better. Splitting data into a drying and a rewetting section did not work well. Moisture content was either underestimated in summer and overestimated in winter or overestimated all the time (Fig. 2). The best way to simulate moisture content was to flatten the model curves by a moving average. Thus the effects of outliers could almost be eliminated.

For the best model (C3), a mean deviance of –0.51% ± 0.71% (R^2adj = 0.616) was found (Eq. 3; Table 5). All of the models, excluding those which were based on a split drying and rewetting section, showed mean deviances between 0.51% and 2.56% (Fig. 3 and Fig. 4). The overall test statistics for each model are given in Table 6.

$$C_{MC} = 2.440 \times 10^{-2} - 1.757 \times 10^{-3} \times T - 4.691 \times 10^{-3} \times DP + 1.359 \times 10^{-2} \times P \quad (3)$$

C_{MC} = change in moisture content (%/day)
T = mean day temperature (°C)
DP = mean daily potential of relative humidity (%)
P = sum of liquid and non-liquid equivalents of daily precipitation (mm)

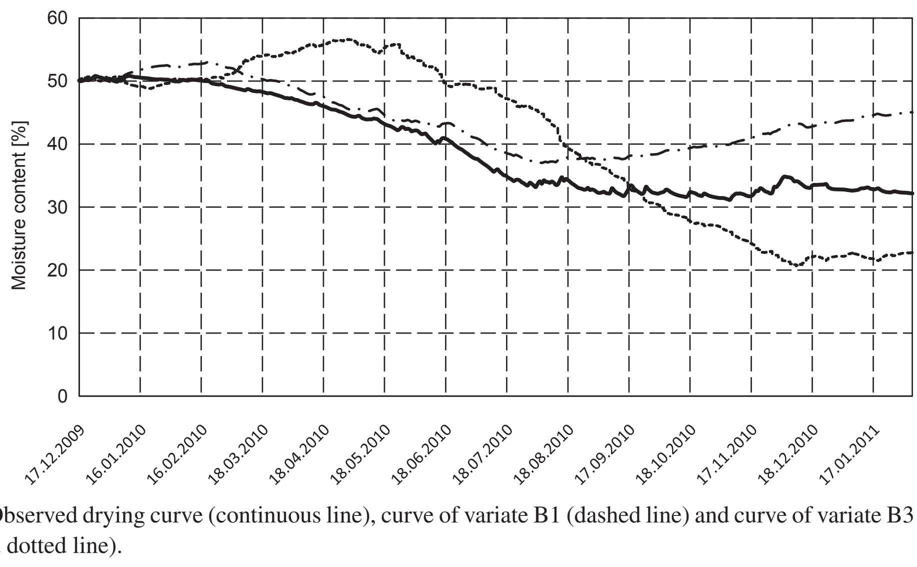

Fig. 2. Observed drying curve (continuous line), curve of variate B1 (dashed line) and curve of variate B3 (dashed and dotted line).

Table 5. Parameters estimate, Student's t-test and summarized test statistics of model variate C3.

Coefficients:	Estimate	Std. error	t-value	p-value
Intercept (Int.)	0.0243960	0.0072004	3.388	0.000772
T	–0.0017572	0.0003988	–4.407	1.34×10^{-05}
DP	–0.0046917	0.0003381	–13.878	$<2\times10^{-16}$
P	0.0135909	0.0012047	11.282	$<2\times10^{-16}$

Residual standard error: 0.05661 on 407 degrees of freedom
Multiple R^2: 0.619, Adjusted R^2: 0.6162
F-statistic: 220.4 on 3 and 407 DF, p-value: $<2.\ 2\times10^{-16}$

Table 6. Test statistics and parameters estimates of all model variates. Variates with "dr" for "drying" or a "w" for "wetting" consist of two separate equations for drying and rewetting. Their results are summed up to estimate the change in moisture content.

Variate	Intercept	T	DP	P	WS	R^2adj	p-value
A1	3.173×10^{-03}		-2.962×10^{-04}	2.822×10^{-02}	-5.052×10^{-03}	0.439	$<2.2\times10^{-16}$
A2	4.755×10^{-03}	-1.066×10^{-04}	-2.961×10^{-04}	2.758×10^{-02}	-5.018×10^{-03}	0.410	$<2.2\times10^{-16}$
A3	0.0349081		–0.0061882	0.0154821		0.438	$<2.2\times10^{-16}$
A4	0.0590837	–0.0023562	–0.0060095	0.0153929		0.417	$<2.2\times10^{-16}$
B1dr	-3.558×10^{-04}	-4.356×10^{-04}	-1.353×10^{-04}	-5.550×10^{-03}	-5.834×10^{-03}	0.332	$<2.2\times10^{-16}$
B1w	5.568×10^{-03}	1.038×10^{-03}	-2.122×10^{-04}	2.778×10^{-02}		0.513	$<2.2\times10^{-16}$
B2dr	-4.442×10^{-04}	-4.294×10^{-04}	-1.356×10^{-04}	-5.547×10^{-03}	-5.837×10^{-03}	0.331	$<2.2\times10^{-16}$
B2w	8.413×10^{-03}	8.434×10^{-04}	-2.010×10^{-04}	2.706×10^{-02}		0.474	$<2.2\times10^{-16}$
B3dr	–0.0453584	–0.0046363	–0.0021021			0.385	$<2.2\times10^{-16}$
B3w	0.161008	0.004891	–0.005752	0.007334		0.144	0.0001948
B4dr	0.0453584	–0.0046363	–0.0021021			0.385	$<2.2\times10^{-16}$
B4w	0.181846	0.003838	–0.005723	0.006651		0.120	0.0007908
C1	1.438×10^{-03}	-7.996×10^{-05}	-1.753×10^{-04}	3.170×10^{-02}	-5.740×10^{-03}	0.594	$<2.2\times10^{-16}$
C2dr	-4.034×10^{-04}	-4.399×10^{-04}	-1.206×10^{-04}	-7.004×10^{-03}	-6.251×10^{-03}	0.377	$<2.2\times10^{-16}$
C2w	4.297×10^{-03}	9.263×10^{-04}	-1.495×10^{-04}	3.220×10^{-02}		0.622	$<2.2\times10^{-16}$
C3	0.0243960	–0.0017572	–0.0046917	0.0135909		0.616	$<2.2\times10^{-16}$
C4dr	–0.0531955	–0.0049506	–0.0016582			0.466	$<2.2\times10^{-16}$
C4w	0.197675	0.005243	–0.006365	0.010823	–0.157956	0.284	5.978×10^{-08}
D1	-2.124×10^{-02}		-4.881×10^{-05}	2.823×10^{-02}	-8.604×10^{-04}	0.439	$<2.2\times10^{-16}$
D2	0.0349081		–0.0061882	0.0154821		0.438	$<2.2\times10^{-16}$

3.3 Sensivity Analysis

Sensitivity analysis was carried out to test which of the input variables had the strongest impact on drying. It showed that the drying potential of the relative humidity and therefore the relative humidity itself, had the strongest effect on drying. Air temperature and precipitation have less impact on explaining the drying process (Table 7). As expected, a negative correlation between relative humidity and air temperature (–0.426) was observed. Correlations between air temperature and precipitation (0.067) and between precipitation and relative humidity (0.274) were not strong.

3.4 Simulation of a Cover

Investigating the effect of covering, the simulation showed that although the strong effect of relative

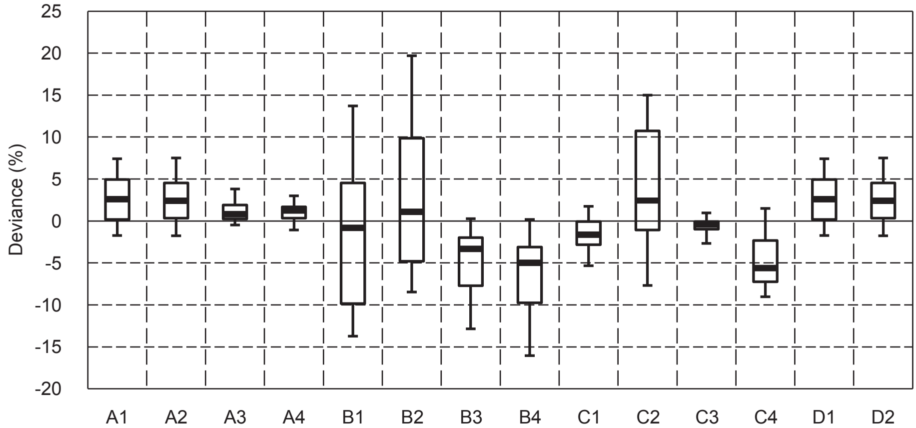

Fig. 3. Boxplot of all variates, showing mean deviances from the observed curve and the respective maximum deviances from the observed curve. The rectangle outlines the first (25%, lower end) and the third quartile (75%, upper end). The black strip in the middle is the median. The brackets outline maximum deviations in both directions.

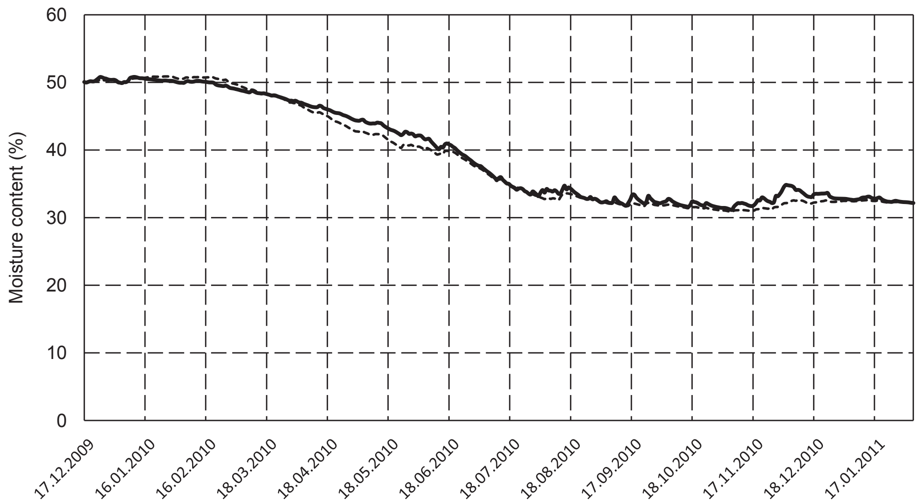

Fig. 4. Observed drying curve (continuous line) and curve of selected variate C3 (dashed line).

Table 7. Sensitivity analysis of the input variables for selected variate C3: R^2adj after stepwise removing of variables according to their impact on the model.

Variable removed	R^2adj
None	0.6162
Air temperature	0.5989
Precipitation	0.4979

humidity was still included, the pile would have dried to a moisture content of 18.0% in the end, instead of 32.2%. Thus the difference is 14.2%, caused by the effect of covering. Including the effect of precipitation seeping through the cover to achieve more reasonable reductions of moisture content, it showed, provided that seeping was constant, that 1.5 mm day^{-1} up to 2 mm day^{-1} would have to seep through the cover to achieve reasonable reductions of 3%–6%.

Table 8. Revenues from interest yielding (revenue plus interest at the end of the month) compared to revenue from drying, if delivered at each month's moisture content. Results are given based on one ton air-dry (ton aid) for better comparability. Pricing is based on tons of absolutely-dry (abd) material. Further, respective heating values are displayed.

Month	Ton aid	Ton abd	Moisture content	Heating value	€ ton abd^{-1}	Revenue drying	Interest revenue (I)
April	1	0.539	46.1%	2.53 kWh kg^{-1}	92 €	49.59 €	49.67 €
May	1	0.566	43.4%	2.69 kWh kg^{-1}	92 €	52.07 €	49.76 €
June	1	0.595	40.5%	2.87 kWh kg^{-1}	92 €	54.74 €	49.84 €
July	1	0.646	35.4%	3.17 kWh kg^{-1}	92 €	59.43 €	49.92 €
August	1	0.664	33.6%	3.28 kWh kg^{-1}	96 €	63.74 €	50.01 €
September	1	0.675	32.5%	3.34 kWh kg^{-1}	96 €	64.80 €	50.09 €

3.5 Heavy Rainfall

When testing the second assumption on heavy rainfall, it revealed that events of 30 mm to 35 mm a day can cause a rise in moisture content up to 0.9%. Generally speaking, the effect declined rather fast after the rainfall event. Given that, as observed, a heavy rainfall event is followed by other, smaller ones, it took up to one week to revert to the same moisture content that existed prior to the event. If no further rainfall would have followed, the previous moisture content could have been achieved within estimated 2 to 3 days.

3.6 Economic Benefit

The third assumption considered natural drying to be effective enough to succeed not only in terms of drying performance, but also in terms of economical benefit. For the duration of the trial the heating value (HV) increased from 2.53 kWh kg^{-1} to 3.34 kWh kg^{-1} and the moisture content decreased from 46.1% (April) to 32.5% (September). Therefore the price for delivered fuel wood rose from 88 € ton abd^{-1} to 96 € ton abd^{-1}. Revenue of the drying variate exceeded the interest variate by 14.71 € per ton aid in September (Table 8). Taking harvesting cost into account reduces the revenue from drying by 0.31 € ton aid^{-1} (from 64.80 to 64.49) and the difference between drying and yielding interest reduces to 14.40 € ton aid^{-1}.

4 Discussion

Observation of the moisture content is quite common in any study concerning biomass for energy uses. Attempts to simulate the change in moisture content have already been made in several studies. Different kinds of approaches, featuring diffusivity equations (Gigler et al. 2000) or linear or non-linear multi regression models focusing on different explaining variables are to be found in scientific literature. A main outcome of this study is a way to operationalize this procedure. For practical use, rather easy and cost saving input is crucial. For this reason the study focused on wind speed, air temperature, precipitation and relative humidity, like Kröll (1978) suggested. A multi regression model based on daily averages and sums was used. Gaining data is rather easy, especially when use at a centralised storage place is considered. Contrary to the model of Filbakk et al. (2011) no data on the logs is necessary, except the species. Further, more empirical data and repetitions will be necessary to parameterise the model.

Natural wind drying is highly dependent on the location where the pile is set up. The low mean and maximum wind speed indicate a rather unexposed position of the pile. Truly, the pile was surrounded by fire wood piles in the south and west. A more open location probably would have had advantages in drying performance. Due to the use of the area as a large storage area, this was the most open and exposed location. The results of other studies that described a uniform drying of the pile, or a poor drying of the lower section (Gigler et al. 2000, Filbakk et al. 2011) could not be confirmed. It can be assumed that the better access for wind to the lower sections, because of the elevated metal frame, caused this effect. In practical use, one could achieve elevation by using two or three logs with the other logs piled crosswise on them. Kofman and Kent (2009) too suggest off-ground storage for better wind access.

The absolute decrease within one year in moisture content is similar to other studies (Röser et al. 2010). Considering the drying period from the start until the lowest moisture content in November, alike moisture contents of 33% for European black pine [*Pinus nigra*] after drying from May to September (Golser et al. 2005) and of just under 30% for Scots pine [*Pinus sylvestris* (L.)] from May to August are reported (Nurmi and Hillebrand 2007). Most of the drying effect occurred in that period (decrease of 12.4%).

Rewetting of 1.6% took place in November. The change in pile weight could have occurred because of snowfall, but interestingly no snowfall was recorded at this point. Thus the increase in weight and moisture content had to be caused by rainfall and thus by a higher relative humidity. Therefore the rewetting of the pile could not be counterbalanced by drying. Other studies (Nurmi 1995, Nurmi and Hillebrand 2007) reported higher rates of rewetting, up to 5%–6%. A possible reason for the fewer rewetting in this case could have been the rather warm temperature for November, ranging from 5 °C to 11 °C.

A point to consider in the model formulae and for a future revision is the rise in moisture content when negative values in temperature occur. Contrary to what one would expect almost no overestimation of the moisture content occurred.

Considering the difference in moisture content between observation dependent on pile mass and laboratory analysis one possible reason for this could be the loss of bark when manipulating the logs at the end of the experiment. It can be assumed that the lack of bark in moisture content analyses at least partially caused this effect.

The sensitivity analysis proved that relative humidity has a significant effect on the drying performance, as reported earlier (Gigler et al. 2000, Filbakk et al. 2011). Temperature and precipitation showed lesser effect on rewetting. The latter was to be expected (Gigler et al. 2000). Contrary to the findings of Kofman and Kent (2009), wind speed did not prove to be significant in this study. A possible reason for this is the rather unexposed location. Sun and thus radiation was not measured, but it could complete the set of input variables in future.

The simulation of the effect of covering the pile showed that although the dominating effect of relative humidity was still included in the model, the pile would have dried to lower moisture content. 18.0% instead of 32.2% seems not reasonable under field conditions, but it gives a notion of the general direction. The simulation of the covering certainly does not include the effect of harder drying, when approaching lower moisture content. Therefore, and because of the effect of precipitation seeping through the cover or wetting from the side, the impact of covering stated in other studies, ranging from 3% to 6% (Jirjis 1995, Nurmi and Hillebrand 2007), can be considered reasonable. Furthermore one has to take in account that because of the lack of empirical backup data this outcome can only be considered a rough estimation.

The findings on heavy rainfall in part do not completely correspond with other studies that stated that there is almost no effect of heavy rainfall on the drying performance (Gigler et al. 2000). It can be assumed that both Scots pine and willow are only wet superficially, but Scots pine can be considered more likely to hold water back in its rough bark than the smooth willow. Concluding, a longer delay than more than a few days in the point of chipping is not likely. As stated in other studies (Nurmi and Hillebrand 2007, Petterson and Nordfjell 2007, Röser et al. 2010) this is mostly dependent on regional climate conditions. However, in any case covering the pile could help to prevent any of these effects.

Economic analyses showed that drying can be beneficial to the outcome in financial terms. Other findings may be possible, depending on the market conditions in other areas.

The models must only be used within the range of the explanatory variables studied as shown in Table 4. Further similar conditions (like elevation of the pile) are crucial.

5 Summary

The main objectives of the current study were to investigate the dominating parameters of natural drying and model the change of moisture content depending on simply measureable input components, like wind speed, air temperature, relative humidity and precipitation, as a trial for future implementation in practical use. Further, the effect of heavy rainfall on the drying performance and the economic benefit of drying were evaluated.

An experimental design was set up to gain empirical data. The drying curve of a pile of logwood and the corresponding meteorological parameters were observed. These data served as input for a multiple linear regression model.

A model for the simulation of change in moisture content could be found, based on the daily means of temperature, drying potential of the relative humidity and the daily sum of precipitation. A mean deviance of –0.51% ± 0.71% is less than any practical use necessitates.

Further, the impact of heavy rainfall events on a logwood pile could be estimated. Generally speaking, a delay of 2–3 day in chipping is what is required to revert to pre-rainfall moisture content, if an event of over 30 mm a day occurs.

In terms of economic benefit, drying can be beneficial, depending on the market conditions in the considered area.

It proved that working with a data logger and an automatic transfer to a server worked well, without any disruption. For practical use, this transfer is very important for a prediction method to work. Further the experimental design with the metal frame and the meteorological station proved to be well-thought-out. Only small enhancements will have to be made, such as including a heating unit in the measuring pitcher, for a better measurement of non-liquid precipitation. Further, a radiation measuring unit could be added. Repetition of this experiment will have been carried out to gain more experimental data.

In future the similar models could be applied to practice, especially on larger landings, like those at pulp mills and chip board plants. The model parameters will have to be adjusted for other tree species and parameterized for the site of operation.

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