Original scientific paper

Comparing Two Different Approaches in Modeling Small Diameter Energy Wood Drying in Logwood Piles

Gernot Erber, Johanna Routa, Marja Kolström, Christian Kanzian, Lauri Sikanen, Karl Stampfer

Abstract

Moisture management is a key element to improving the cost-efficiency of energy wood supply, through the whole supply chain. Numerous studies of natural drying of forest biomass have been carried out based on traditional sampling of piles or weighing. The latest methodology for monitoring moisture changes has been continuous weighing of biomass in racks built on load cells. The aim of this study was to develop accurate drying models in Austria and Finland for small diameter logs and test the exchangeability of the developed models between countries. Overall drying periods were December 2009 to February 2011 for Austria and March 2012 to June 2013 for Finland. Moisture content dropped from 50.1% to 32.2% (Austria) and from 62.2% to 38.6% (Finland) during the drying periods. Drying performance was evaluated for the period April to October. Two different types of models were developed and the results were cross validated. It proved to be possible to fit satisfactory accurate drying models within the target deviation of ± 5% using both approaches. Whereas the Austrian approach is based on a more basic set of variables, the Finnish approach combines the variables within one. Both approaches are justified depending on the available data.

Keywords: fuel wood drying, drying modeling, logwood piles, meteorological models

1. Introduction

Biomass fuel quality is often defined by the calorific value. Lower moisture content results in increasing calorific value (Hartmann and Kaltschmidt 2001, Stokes et al. 1987). Drying in piles can help to decrease significantly the moisture content of energy wood within a short period of time (Erber et al. 2012). Depending on conditions during the drying period, whole trees and logwood are likely to lose 20% to 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).

An advantage of drying logwood is low dry matter loss compared to drying logging residues or forest chips. Golser et al. (2005) report 2% dry matter losses per year for Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.). Dry matter losses can be caused either by microbial activity, most commonly fungal attacks (biological), or spillage of material during handling and storage (technical)(Pettersson and Nordfjell 2007). Drying of logwood for energy purposes is also economically beneficial. Erber et al. (2012) reported a gain in income of 14.40 € per air dry ton compared to yielding interest after having sold the material without drying.

Drying in windrows by convection is a process governed by temperature, relative humidity, wind speed and rainfall (Kröll 1978). Kofman and Kent (2009) commented that wind and sun exposure are the most important factors for drying. Stokes et al. (1993) list a large variety of drying techniques, including transpirational air drying and foliage on un-delimbed logs, which can be used to improve drying performance.

The idea of using drying models to predict moisture content alteration first appeared in the 1980.

Stokes et al. (1987) presented drying models for soft and hardwoods, for loblolly pine (*Pinus taeda* L.), oak (*Quercus* spp.), sweetgum (*Liquidambar* spp. L.) and red maple (*Acer rubrum* L.) bundles in south eastern USA. Their goal was to model weight reduction through drying using non-linear models. These included weather data like the total daily precipitation and the average daily air temperature. Days since felling, diameter at breast height as well as species and further variables were also considered. Different equations were provided for each season of the year. Depending on the species, different variables (days since felling, total rainfall, original weight of the bundle) were found to be the best predictors. Liang et al. (1996) developed a model for Leucanea (*Leucaena leucocephala* (Lam.) de Wit) including days since drying, initial moisture content, cumulative precipitation and potential evaporation. Gigler et al. (2000) chose a different approach: a model, considering a willow (*Salix viminalis* L.) log as a »non-shrinking, infinite long cylinder of homogenous wood material surrounded by bark«, where any radial water transport depended on different diffusivities of wood and bark. Murphy et al. (2012) stored Sitka spruce (*Picea sitchensis* (Bong.) Carr.) logwood and energy wood in Ireland and developed drying models for off-forest storage. Moisture content loss over a 10 day period was related to the moisture content at the start of the interval, to cumulative precipitation and evapotranspiration for the period, woody biomass type and type of cover. Filbakk et al. (2011) developed a model for whole tree drying in piles, focusing on explanatory variables like days of storage, harvesting season, location, climatic conditions and position in the pile, tree species and relative crown length. Model by Erber et al. (2012) for pine logwood predicted daily alteration in moisture content based on mean daily temperature and relative air humidity and the daily sum of precipitation. Relative humidity was found to be the most important factor for drying. Similar to Murphy et al. (2012), Dong Wook and Murphy (2013) developed drying models for Douglas Fir (*Pseudotsuga menziesii* (Mirb.) Franco) and hybrid poplar (*Populus* spp.) in Oregon using linear mixed effects models. Again a 10 day period was chosen to predict moisture content alteration depending on cumulative precipitation and evapotranspiration. Material size was a further variable. It was concluded that, due to the logical variation of drying with the climatic pattern of a region, these models can be extended to other regions of Oregon, too.

Based on previous studies, the specific research objectives of this study were: 1) to develop climate based drying models for two different piles of pine logwood in Austria and Finland in the spring to autumn period, using two different approaches developed in Austria and Finland based on data collected during two former experiments; 2) to investigate the exchangeability of the developed models between the countries.

2. Materials

The data for this comparison of modeling approaches was derived from two recently completed drying experiments. Details on the Austrian study are given in Erber et al. (2012). In this paper moisture content is expressed on wet basis, as the ratio (in percent) of the water weight and the total weight of the woody biomass.

2.1 Study sites

The two experimental sites in this study were located in Austria and Finland. The Austrian site (47°17'N, 15°58'E; 350 m above the Adriatic) was in Hartberg, the province of Styria. The Finnish site was in Ilomantsi (62°46'N, 30°58'E; 150 m above Helsinki

Fig. 1 Study sites in Finland (left side) and Austria (right side) showing the experimental design

level). Both sites were off forest study sites. The Austrian site was a timber yard, the Finnish site a storage area at a research station (Fig. 1).

2.2 Materials

To monitor the change in moisture content through the change in weight, metal racks on load cells were used at both sites. Pine logs with average diameters of 15 cm and lengths of 4 m to 5 m were investigated. Details on the material are given in Table 1. Disc samples (three per stem) were taken by chainsaw in the beginning to measure the initial moisture content in the laboratory.

Table 1 Parameters of the material and experimental site

Parameter	Austria	Finland
Total number of logs	208	~ 150*
Average length, m	4.72 m ± 0.50	~ 4 m ± 0.4*
Average diameter, cm	15.2 cm ± 5.3	~ 15 cm ± 5*
Number of sample logs	42	6
Initial moisture content (analysis), %	47.2	61.5
Initial total load, kg	16 670	11 710
Elevation of the first layer above ground level, cm	30	45
Ground material	soil and gravel	gravel

* Estimated parameters

2.3 Modeling data

Weather data was recorded at both sites. Average daily moisture content (MC, %) of the piles, wind speed (WS, m s^{-1}), relative humidity (RH, %) and air temperature (TC, C°) and the daily sums of precipitation (P, mm), and solar radiation (R, W m^{-2}) were selected from the data pool. In order to calculate reference evapotranspiration (ET_0) according to the universal standard of the FAO Penman-Monteith method (Allen et al. 1998), further data on daily minimum and maximum air temperature and dew point temperature were provided. Net evaporation (net, mm) was calculated by subtracting precipitation from the reference evapotranspiration. Whereas Austrian data on precipitation and solar radiation originated from the study site, Finnish data was partly provided by weather radar (precipitation) and a grid based model (10 km x 10 km, solar radiation). Air temperature data was converted to Kelvin (TK) to avoid ambiguous effects for temperatures around 0 °C.

The analysis was carried out in the period April 1 to October 31, because during this period there was no snow at Finnish site. Snow cover on the pile affects the weight, causing confusion in the determination of the moisture content of the material. The Austrian dataset was developed in 2010, and the Finnish in 2012.

2.4 Modeling approaches

The Austrian approach can be considered as a »cumulated sum approach«. The cumulative alteration in moisture content is calculated by a multiple linear regression using cumulative sums of daily means of air temperature, wind speed, relative humidity and daily sums of precipitation. Therefore, the model delivers moisture content alteration over a period in daily steps. In contrast, the Finnish model only uses the daily sum of net evaporation as input variable in its linear regression model. Daily alteration in moisture content is the dependent variable. These values can be cumulated afterwards for a specified period of time.

The recorded dataset was split into half using random numbers. One half was assigned to be the analysis set, whereas the other was assigned to be the testing set for the developed model.

2.5 Model comparison and cross validation

The main criteria for the accurateness of the models were their mean deviation, respective standard deviation and median deviation from the observed curve. A deviation of moisture content of up to ± 5% was considered a reasonable model.

The models were applied to the full dataset of the other trial to investigate the validity for other regions.

2.6 Valid range

The valid range of the models for any further use depends on the data the models were developed from. The limits applied were the 10% and 90% quantile for all variables. The models shall only be used for small diameter (10 cm to 20 cm) and 4 m to 5 m long pine logwood during the period April to October. Respective limits for daily averages and sums of the input variables are given in Table 2.

3. Results

3.1 Austrian approach

»Cumulative sume« approach proved to work well for both datasets. Mean deviations of moisture content from the observed curve were 0.07% ± 0.49% (Austrian data) and –0.02% ± 0.46% (Finnish data), respectively. The median deviations were both 0.10%. Residual standard errors were 0.51% and 0.44%. Both R^2 ad-

Table 2 Limits for the valid range models based on Austrian and Finnish data: 10% and 90% quantile on daily basis

Basis	TC, °C	RH, %	P, mm	WS, m s^{-1}	Net, mm
10% Austrian based	7.02	34.45	0.00	0.26	–5.73
90% Austrian based	21.83	89.84	9.03	0.79	4.08
10% Finnish based	0.43	57.00	0.00	1.38	–4.14
90% Finnish based	16.90	95.25	8.44	4.34	4.67

Table 3 Parameters estimate, Student's *t*-test and summarized test statistics for the Austrian data based cumulative sum model

Coefficients	Estimate	Std. Error	*t* value	*p* value
Intercept	1.332	1.168 x 10^{-1}	11.40	< 0.001
WS	–5.452 x 10^{-2}	1.977 x 10^{-2}	–2.76	0.0063
RH	5.224 x 10^{-3}	2.821 x 10^{-4}	18.52	< 0.001
TK	–1.283 x 10^{-3}	9.101 x 10^{-5}	–14.10	< 0.001
P	4.471 x 10^{-3}	1.381 x 10^{-3}	3.23	0.0014

Residual standard error: 0.507 on 209 degrees of freedom
Multiple *R* squared: 0.991, Adjusted *R* squared: 0.991
F statistic: 5 788 on 4 and 209 DF, *p* value: < 0.001

Table 4 Parameters estimate, Student's *t* test and summarized test statistics for the Finnish data based cumulative sum model

Coefficients	Estimate	Std. Error	*t* value	*p* value
Intercept	1.130	9.576 x 10^{-2}	11.80	< 0.001
WS	6.851 x 10^{-3}	4.262 x 10^{-3}	1.61	0.110
RH	8.585 x 10^{-3}	1.177 x 10^{-4}	72.93	< 0.001
TK	–2.940 x 10^{-3}	6.561 x 10^{-5}	–44.82	< 0.001
P	1.896 x 10^{-2}	1.512 x 10^{-3}	12.54	< 0.001

Residual standard error: 0.444 on 209 degrees of freedom
Multiple *R* squared: 0.994, Adjusted *R* squared: 0.994
F statistic: 8 962 on 4 and 209 DF, *p* value: < 0.001

justed were 0.99. Contrary to the Austrian data based model, wind speed was not found significant in the Finnish data based model (Tables 3 and 4; Fig. 2).

3.2 Finnish approach

The net evaporation approach, given in Table 5 and 6, provided a satisfactory outcome, but was not as accurate as the Austrian approach. Mean deviations of moisture content from the observed curve were –1.04% ± 1.43% (Austrian data) and 0.52% ± 0.87% (Finnish data), respectively. The median deviations were 0.32% and –0.03%. (Fig. 2).

Table 5 Parameters estimate, Student's *t* test and summarized test statistics for the Austrian data based net evaporation model

Coefficients	Estimate	Std. Error	*t* value	*p* value
Intercept	0.062	0.013	4.931	<0.001
net	0.020	0.002	10.137	<0.001

Table 6 Parameters estimate, Student's *t* test and summarized test statistics for the Finnish data based net evaporation model

Coefficients	Estimate	Std. Error	*t* value	*p* value
Intercept	0.039	0.013	2.86	4.648 x 10^{-3}
net	0.062	0.003	19.42	<0.001

3.3 Cross validating

Applying the derived curves to each other's dataset did work well for three of the four modeled curves. For the use of the Austrian approach model, derived from Finnish data, on the Austrian data, a mean deviation of moisture content was –24.24% ± 13.09%. The Austrian approach model, derived from Austrian data, underestimated the drying performance of the Finnish pile (mean deviation of 1.27% ± 1.02%). The models based on net evaporation performed well – the Austrian data-based model underestimated the drying performance of the Finnish pile (mean deviation 2.32% ± 1.63%), and the Finnish data-based model varied strongly in its spring and summer estimates (mean deviation –0.68% ± 1.97%) (Fig. 3).

4. Discussion

Similar to other studies (Stokes et al. 1987, Liang et al. 1996, Murphy et al. 2012, Filbakk et al. 2011, Erber et al. 2012, Dong-Wook and Murphy 2013), depending on the modeling approach, climatic conditions such as wind speed, precipitation, relative humidity and air temperature or precipitation and evapotranspiration were found to govern the drying process. Three of the developed models are plausible. The model developed from Finnish data using the Austrian approach assigns a – illogical – positive prefix to wind speed. Cross validation clearly showed that the use of these coefficients produces an absolutely unacceptable output. Therefore, it has to be concluded that this model is totally wrong

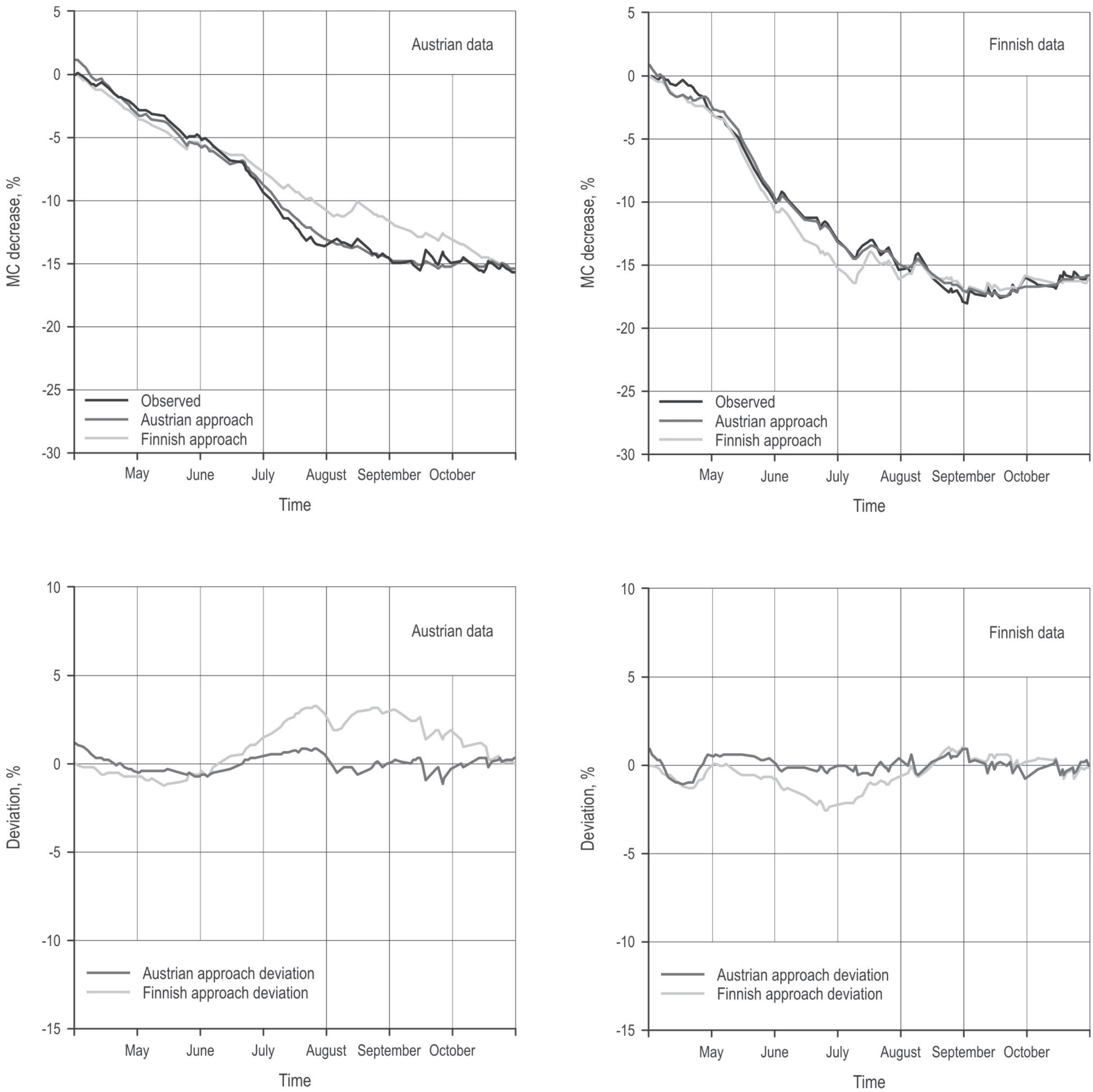

Fig. 2 Above: observed (solid lines) and modeled moisture content decrease curves (dashed and dashed dotted lines) for Austrian and Finnish data. Below: respective deviations from the observed curves with a target deviation of ± 5% (solid lines)

and should not be used by any means. Wind speed and air temperature govern drying, whereas precipitation and relative humidity govern rewetting.

Some details have to be considered when trying to evaluate these models. The Finnish data had three different origins – the meteorological station at Mekrijärvi research station, the weather radar for precipitation and a grid based model for solar radiation. The Austrian data originated almost exclusively from the drying site. Only solar radiation was obtained from a nearby state-run meteorological station. Longwave and shortwave radiation for the Penman-Monteith equation were derived from this measurement. This is probably the explanation for a greater variation of deviation of the Austrian data based model around the observed curve. The Finnish data based model fit its pile better.

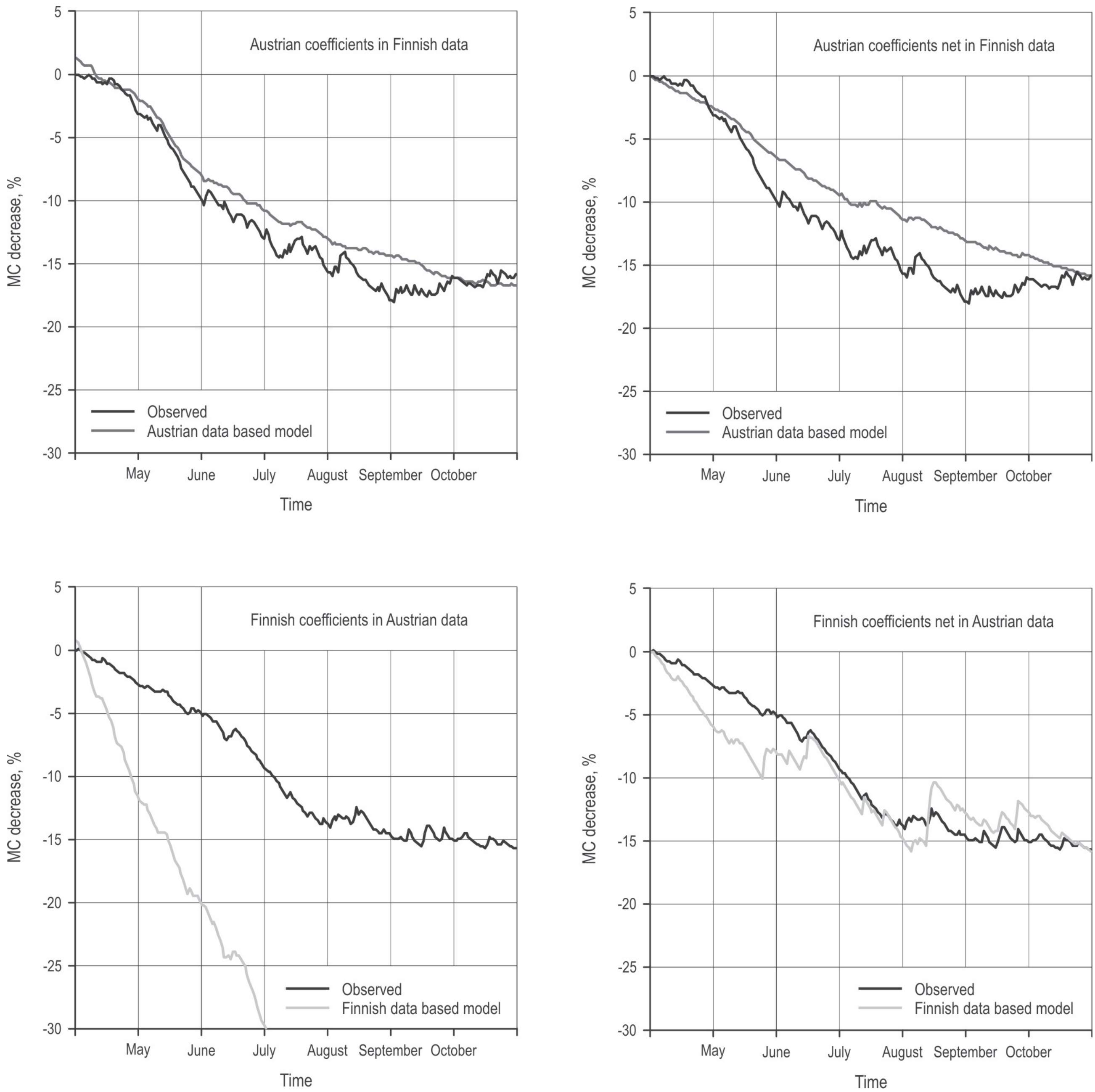

Fig. 3 Above: observed (solid lines) and modeled moisture content decrease curves (dashed lines) for Finnish data applying Austrian data-based models. Below: observed (solid lines) and modeled moisture content decrease curves (dashed-dotted lines) for Austrian data applying Finnish data-based models

Similarity in experimental design can be a point of concern. Though both experiments used metal frames on load cells, the experimental design differed in some details. At the Finnish site, a paper cover was used at the sides and the bottom to simulate natural drying conditions. Such a cover was not used at the Austrian site. The limitations in wind exposure were probably the reason why the wind speed was not insignificant in the Austrian approach and Finnish data based model.

The use of similar material is crucial, too. Though the average diameter and length are alike, different wood densities could affect the drying performance. No analysis of wood density was carried out at the Finnish site. Hence the comparison was not possible.

Applying and trying to cross validate the models on each other's dataset proved to be satisfactory. Only one of the four models did not reasonably fit. The different valid range (Table 2) of the models can be a major factor here. The Austrian approach model based on Austrian data works well in the Finnish dataset because it covers all the range of temperature and precipitation and almost all of relative humidity range. Only Finnish wind speed data is completely out of range. The Finnish data based model does not cover all of the Austrian temperature and relative humidity range. Especially low relative humidity and high temperature conditions – best fitted for drying – are not covered by this model. Finally, wind speed is completely out of range. Furthermore, wind speed was not significant within the Finnish model.

When looking at the net evaporation approach models, a wider range of the Austrian data based model can be observed. However, satisfying accuracy was achieved for both models. The Finnish data based model showed weaknesses in prediction during spring and autumn. Approximated longwave and shortwave radiation in the Austrian data can be considered the reason for the less accurate prediction.

5. Conclusions

It proved to be possible to fit accurate drying models within the target deviation of ± 5% using both approaches. Whereas the Austrian approach is focused on a more basic set of variables, the Finnish approach combines the variables within one. Both approaches are justified – depending on the available data.

When applying drying models to other regions of the earth, accuracy of prediction can be affected by material and storing properties. Models can only be valid for the conditions under which they were developed. This study showed that, if variable values are out of the model range, a reasonable prediction is not possible.

In order to ensure reasonable results, the conditions under which the models have been developed, have to be specified in terms of climatic conditions, storing technique and material type.

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Authors' address:

Gernot Erber, MSc.*
e-mail: gernot.erber@boku.ac.at
Christian Kanzian, MSc.
e-mail: christian.kanzian@boku.ac.at
Prof. Karl Stampfer, PhD.
e-mail: karl.stampfer@boku.ac.at
University of Natural Resources and Life Sciences
Peter Jordan Strasse 82
1190 Wien
AUSTRIA

Johanna Routa, PhD.
e-mail: johanna.routa@metla.fi
Prof. Lauri Sikanen, PhD.
e-mail: lauri.sikanen@metla.fi
Finnish Forest Reseach Institute
Yliopistokatu 6
80101 Joensuu
FINLAND

Marja Kolström, PhD.
e-mail: marja.kolstrom@uef.fi
University of Eastern Finland
Mekrijärvi Research Station
Yliopistontie 4
82900 Ilomantsi
FINLAND

* Corresponding author