Validation of Prediction Models for Estimating the Moisture Content of Small Diameter Stem Wood

Johanna Routa, Marja Kolström, Johanna Ruotsalainen, Lauri Sikanen

Abstract

Moisture is the most important factor influencing the quality and calorific value of fuel wood. Drying models for estimating the optimal storage time based on average moisture change in fuel wood stacks stored outdoors have been developed for different stem wood piles. Models are an easy option for making an estimate of the moisture content of an energy wood pile if compared with sampling and measuring the moisture of samples. In this study, stem wood models were validated against data from forest companies. Fourteen reference piles of covered pine stem wood and 8 piles of uncovered pine stem wood were studied. The results of the validation are promising. The difference between the measured and modelled moisture was on average only 0.3% with covered piles and 2.5% with uncovered piles. The models presented can be implemented in every location in Finland, because the Finnish Meteorological Institute has a database for interpolated meteorological observations covering the whole country in a 10 km x 10 km grid. For international use, model parameters need to be estimated case by case, but it should also be possible to implement the approach itself worldwide.

Keywords: energy wood, quality, storing, natural drying, model validation

1. Introduction

Thinning is a harvesting method mostly used in Europe and within plantations all over the world. Thinning wood is a typical raw material for the pulping industry as well as for energy and biorefining in the Nordic countries. Especially in Finland, thinning wood from young stands has been increasingly used for energy. In 2010–2013 it was the major source of forest chips for energy (Torvelainen et al. 2014).

Increased use of forest biomass for energy and rising transportation costs are forcing biomass suppliers towards better moisture content (MC) management in the supply chain. Biomass fuel quality is often defined by the calorific value, and lower moisture content results in increasing calorific value (Hartmann and Kaltschmidt 2001, Stokes et al. 1987). Natural drying is used to reduce the moisture content of energy wood after cutting and during storage. Storing time at the roadside depends on the need for energy wood. The supply of energy wood operates year round, but the demand is notable from October to March (Andersson et al. 2002).

After tree cutting, wood starts to react with the surrounding microclimate (Routa et al. 2015). In Nordic conditions, the moisture content of wood drops rapidly in the spring. In late August and September, evaporation usually decreases, and the moisture content of the wood increases. In some cases, it can even be higher than the »green« moisture right after cutting. Maximizing natural drying and minimizing re-moistening are key elements in the quality management of energy wood (Routa et al. 2012). The timing of the operations in relation to the seasons is crucial in order to maximize the quality and monetary value of the energy wood.

In natural drying, the weather conditions are a very important part of the drying process. The most important parameters are evaporation, precipitation, humidity, temperature, solar radiation and wind conditions (Routa et al. 2015). In addition, the material, size and shape of the energy wood pile and the location of the pile, also affect the drying process.

The latest research methodology for monitoring moisture change has been the constant weighing of piles in racks built on load cells (Erber et al. 2012, 2014).This methodology allows moisture changes to be monitored in much more detail than previous sampling methods. The method also gives the moisture of the whole pile, which is challenging in determening the use of sampling methods (Röser et al. 2011). Measurements can be taken automatically and as often as needed. This also enables an exact investigation of the effect of weather on energy wood storage and its moisture content.

In the 1980s, the first ideas of using models to predict the moisture content of wood were presented. Stokes et al. (1987) published their models for soft and hardwoods in south eastern USA. Also, for example, Liang et al. (1996), Gigler et al. (2000), Filbakk et al. (2011), Murphy et al. (2012), Erber et al. (2012) and Dong-Wook and Murphy (2013) have developed different drying models for different species. All approaches to fuel wood moisture content modelling have one common target variable: moisture contents or rather the alteration in moisture content during a specific period. The alteration can be explained by a large variety of explanatory variables, such as meteorological variables, parameters of storing, material type and duration of storage. Today's practice is to measure the moisture content of wood chips when they arrive at the heating plant, but for efficient planning of operations the information is available too late. With the prediction models, it is possible to have an estimation of the moisture content of fuel in advance and plan supply operations so that the fuel is transported to the heating plant in a timely manner.

The objective of this study was to develop a model to forecast the energy wood moisture content and validate the model. Changes in moisture content were linked to weather conditions and microclimate. The model should be easy to apply to the planning systems in operational stage and that is why the model should be quite simple and quick to calculate. To verify fuel wood drying models, reference piles are a good option. Samples must be taken from the piles, which should consist of similar material as regards assortment and tree species. The models developed were validated against real life data from forest companies.

2. Material and methods

2.1 Experimental design

At Mekrijärvi Research Station of the University of Eastern Finland (62°46′N, 30°59′E), two drying racks for round wood with continuous measuring systems were built for research purposes in March, 2012 (Fig. 1). The purpose of the racks is to simulate energy wood storage at the roadside in the forest after cuttings. The racks are similar to those used on timber trucks to carry logs, and their size is 2.5 m in width, 2.6 m in length and 2.8 m in height. As the piles in the racks are quite small compared with real storage in the field, there are cover papers at the bottom and sides of the racks to avoid them drying too quickly. The small diameter energy wood stems of pine were piled up by a machine into the metal racks at the end of March 2012. In the system, four load cells continuously measure the weight of the pile in the rack. These four cells are connected to a junction box, which is connected onwards to a weighing transmitter. Data of weight are stored in a file that can be utilized for data management.

At the Mekrijärvi Research Station, there is a well-equipped meteorological station operated by the Finnish Meteorological Institute (FMI), which provides data on relative air humidity (%), air temperature (°C), wind speed (m/s), wind direction (°), solar radiation (W/m^2) and rainfall (mm), air pressure (hPa), ground temperature (°C), rainfall intensity (mm/h), visible distance (m), height of clouds (m) and snow depth (cm). The meteorological data is collected by a data logger. The weather data can also be obtained from grid data. The FMI provides gridded weather data for the whole of Finland. This data set consists of weather observations (e.g. temperature, humidity, precipitation), which have been interpolated to a 10 km x 10 km grid using the Kriging interpolation method (Venäläinen and Heikinheimo 2002).

Fig. 1 Drying racks with small diameter stems at Mekrijärvi Research Station

The mean annual precipitation in this area is 668 mm, and the mean annual temperature 2.1 °C. The mean snow depth in the Mekrijärvi area is approx. 45–65 cm in the winter months. In the winter of 2012–2013, snow depth was close to the average and the permanent snow cover period was typical. The drying season (from April to October 2012) was unfavourable for wood drying. The mean temperature (9.5 °C) for these seven months was somewhat lower than the long term average mean temperature (9.8 °C) (Drebs et al. 2002). Most of the precipitation occurred in July (163.8 mm) and June (104 mm), a total of 605.3 mm during the investigation period (Fig. 2), which is almost 50% more than the long term average of 439 mm. In the latter part of the drying season (from April to the beginning of June 2013), the precipitation was in total 156.3 mm. The long term averages (1971–2000) were taken from the nearby station at Ilomantsi Kirkonkylä, because there were no data from the Mekrijärvi station, which was founded in 1999. The Ilomantsi Kirkonkylä station is located only 11.6 km from Mekrijärvi, and therefore represents the same climate conditions.

The moisture content is determined based on weight changes in the energy wood storage pile. When the weight of the pile decreases, the moisture content of the material decreases, and when the weight increases, the moisture content of the material increases. The weight of snow on the pile is a challenge for moisture content estimates, because the weight of snow does not indicate changes in the moisture content of the material.

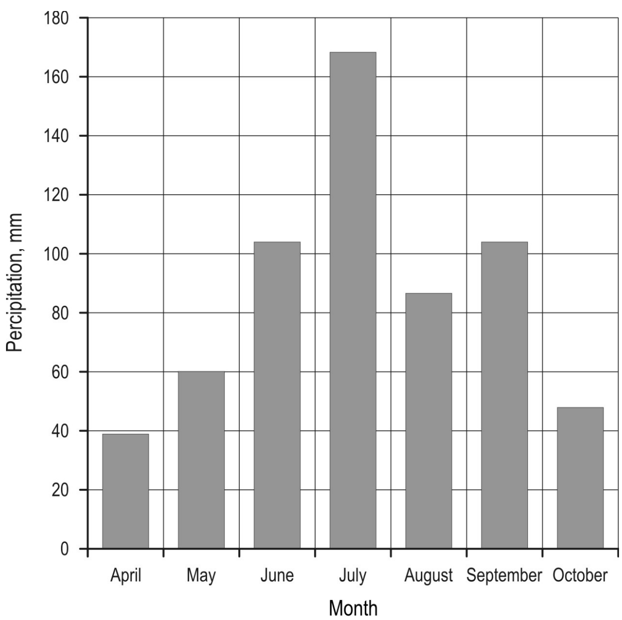

Fig. 2 Precipitation (mm) during the effective drying period at Mekrijärvi Research Station in 2012

2.2 Study material and sampling method

Small size stems were cut at the end of October, 2011. They were piled onto a roadside storage in the field right after cutting. From this storage, the stems were transported to the racks at the research station at the end of March 2012. So the material was in storage for five months under winter conditions in the field.

When the stems were piled onto the racks, six sample stems from each pile were randomly selected. Five of the sample stems were pine and one of them birch. Three sample discs were taken from each sample stem; one from the bottom of the stem, one from the middle of the stem and one from the top of the stem. All of these sample discs were taken because variation of the moisture content within the stem could be significant (Kärkkäinen 2003). In total 18 discs presented one pile in order to determine moisture content at the beginning of the storage period under study. The moisture content (wet basis) was determined using the oven dry method (EN 14774-2). Sampling was carried out in accordance with the solid biofuel standard EN 14778.

The weight changes in these two piles were similar during the summer of 2012. In early September, the other pile was covered with a cover paper manufactured by Walki. The width of the paper was 4 metres. The paper is developed for this purpose, and it should keep the rain and snow away from the pile. The paper can be chipped with energy wood and combusted at a heating plant.

After the storage period, it was assumed that the moisture content varies within the pile. When the piles were unloaded, the material from each pile was chipped using a big drum chipper. The samples for the moisture content analysis were taken from the chips and they were taken from the top, the middle and the bottom of the pile. The fourth sample was a mix of the previous three samples. All the samples were analysed using the oven dry method. At the end of the storage period, we had four measurements of the moisture content per pile.

2.3 Validation data

The validation data for covered small diameter pine stem wood has been collected in central Finland during 2010–2011. The sampled piles were selected so as to represent the average energy wood storages in Finland. The materials of the piles were typical of first thinning. Most of the stands were harvested as an integrated energy and pulpwood harvesting, where all the pulp wood diameter wood (diameter >6 cm) was taken as pulp wood, and the rest of them were collected for

Fig. 3 Moisture samples taken from chip piles

energy wood. All the storage piles were covered with the Walki cover paper. The size of the roadside storages varied from 17 m^3 to 295 m^3. The energy wood was driven to the Äänekoski power plant and chipped there. The moisture samples were taken from piled chips; 6–8 samples were taken with ladle sampling to a big plastic tub. All the samples were spilled onto a table, where they were mixed and then the moisture samples were collected from nine points by hand to a duplicate plastic bag (5 litres). The plastic bags were delivered immediately to the laboratory, where the moisture content was measured using the oven dry method (EN 14774-2). Sampling was carried out in accordance with the solid biofuel standard EN 14778.

Uncovered pine stem wood was delivered by the Tornator Company. The stems were from cuttings made 2–21 months before. Eight test piles were chipped at the Fortum power plant on 10th of November 2014. The moisture samples were taken from the chip piles. Five samples were taken with ladle sampling to a big plastic tub, and all samples were spilled onto a table, where chips were divided into four parts (Fig. 3). One part was put into a duplicate plastic bag (5 litres). Plastic bags were delivered immediately to the laboratory, where the moisture content was measured using the oven dry method. Sampling was carried out in accordance with the solid biofuel standard EN 14774.

2.4 Data analysis

At first, data from continuous measurements was prepared for the analysis. The running mean of the weight of the piles (average of ten previous measurements), the moisture content and the daily moisture change for each day were calculated. The data from 1st of April to the end of October was used, and the winter months were excluded. The weather parameters were interpolated to the grid, and then the evaporation was calculated using the Penman-Monteith equation (Monteith 1981) by the Finnish Meteorological Institute. The interpolation method is explained in detail in Venäläinen and Heikinheimo (2002), except that the precipitation is obtained mainly from the weather radar network and the radiation parameters are nowadays taken from a weather model because of the lack of radiation measurements and synoptic cloud observations. Net evaporation (mm) was calculated by subtracting precipitation from the reference evaporation.

Different modelling approaches were tested; the linear regression model, multiple linear regression model and non-linear model. Temperature, precipitation, evaporation, wind speed and humidity were used as determining variables. Also, net evaporation was tested. Net evaporation means the difference between evaporation and precipitation. In fact, this variable contains all the most important weather parameters that affect energy wood drying.

The target variable is the moisture content alteration per day in % on a wet basis (DMC=daily moisture change). The analyses were performed with IBM SPSS Statistics version 20.

A Mann-Whitney test was used to compare the difference between measured and modelled moisture contents with IBM SPSS Statistics version 20, using the critical level at $p<0.05$. The Mann-Whitney test is considered to be one of the most powerful non-parametric tests especially testing differences in the location of the distribution (Ranta et al. 1992).

3. Results

3.1 Results of modelling

Stand models and roadside storage models for small diameter stem wood were developed using three different approaches: linear regression, multiple linear regression and non-linear regression. In statistics, the non-linear regression model has the best statistical values (Table 1). When these models were applied to validation data of covered pine piles, it was

Table 1 Statistical details of different models

Test values	Linear regression model	Multiple linear regression model	Non-linear regression model
F	784.7	171.3	355.5
p	0.000	0.000	0.000
R^2	0.705	0.726	0.766
Standard error	0.17	0.17	0.15

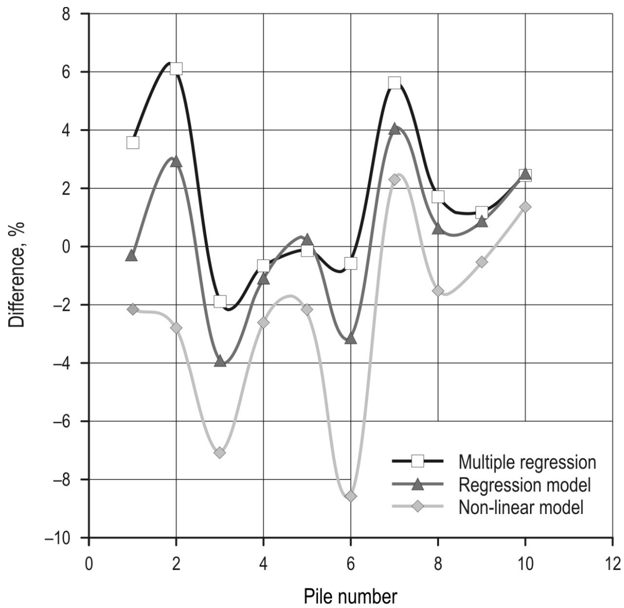

Fig. 4 Difference between measured and modelled moisture with different model types, pine stem wood, covered

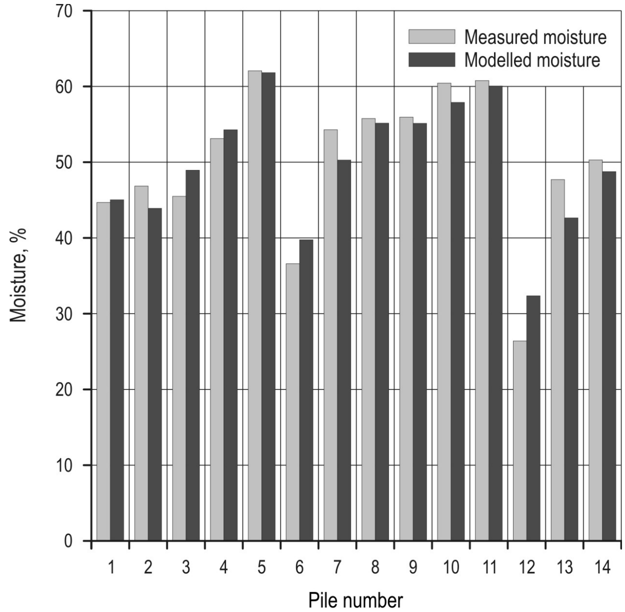

Fig. 5 Measured and modelled moisture content of 14 different covered energy wood piles

Table 2 Drying models for covered and uncovered stem wood stored on roadside

Roadside storage models				
DMC=Coef*(evaporation–precipitation)+const.				
Moisture content (*i*)=moisture content(*i*–1)–DMC				
Model	Coef.	Const.	R^2	SE
Pine birch mix, covered	0.062	0.051	0.70	0.2
Pine birch mix, uncovered	0.062	0.039	0.64	0.2

found that the linear regression model gives the most reliable results (Fig. 4).

Linear regression models were chosen because they appeared to be most functional, and the structure of the model was simple and understandable. For model form, the simplest regression model was chosen with one determining variable, net evaporation (Table 2).

Using the models starts with determining the moisture content of fresh wood. For that reason, average moisture of fresh wood, depending on the cutting month, is presented in Table 3 (Hakkila 1962, Gislerud 1974, Kärkkäinen 1976, Nurmi 1999, Hillebrand and Nurmi 2001, 2007, Nurmi and Lehtimäki 2011 and Routa, unpublished data). After cutting, the stems are stored and the model can be applied to estimate the daily change of the moisture content, and with that estimate the current moisture content of the wood material within the pile.

3.2 Model validation

The moisture content estimation is made by the model acquired from the rack experiment. The result is compared to the moisture content of the reference pile.

3.2.1 Covered stem wood model

The validation results against covered stem wood model are shown in Table 4 and Fig. 5. The difference between the measured and the modelled moisture content varied from 0.4 to 5.95% in 14 different piles.

Table 3 Moisture of fresh stem wood depending on the cutting month in Finland

Moisture content of fresh stem wood, monthly, %												
Species	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Pine	57	57	57	56	56	55	55	57	57	57	57	57
Birch	45	45	45	46	48	42	42	42	42	44	45	45

On average, the difference was only 0.3%. A statistical test was carried out (Mann-Whitney test) and the difference between the measured and modelled value was not statistically significant (p=0.7)

3.2.2 Uncovered stem wood model

The validation results against the uncovered stem wood model are shown in Table 5 and Fig. 6. The difference between the measured and the modelled moisture content varied from 1 to 14% in 8 different piles. On average, the difference was 2.5%. The difference between the measured and the modelled value was not statistically significant (p=0.6). In this experiment, the age of the energy wood piles varied from 2–21 months. It can be seen that the oldest piles, which had been stored during the winter, have the highest difference between the modelled and the measured moisture content. The moisture content of energy wood increases during the winter, when the evaporation is really low, and in springtime melted snow increases the moisture of the pile especially in storage piles without a cover. It is a very site-specific situation, and it is hard to model how much the moisture increases, but the average amount of 5% has been used.

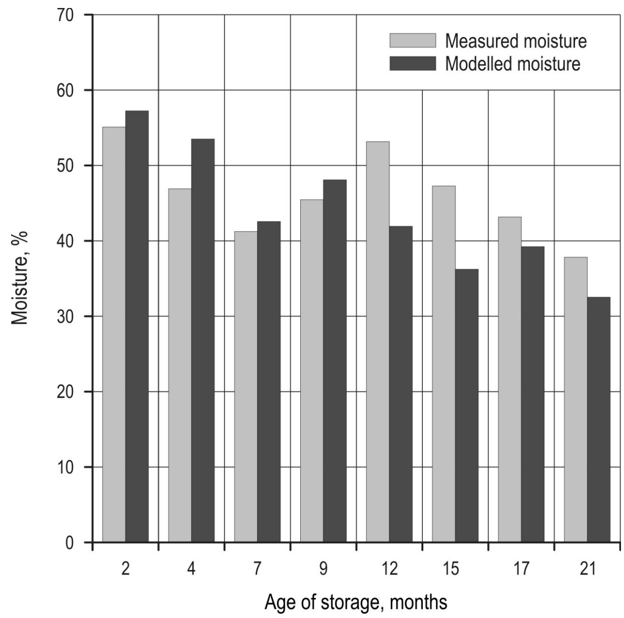

Fig. 6 Measured and modelled moisture content of 8 different uncovered energy wood piles

4. Discussion

In this study, a forecast model for the moisture content of small size stems in roadside storage in both cases, uncovered and covered piles, have been developed. With the detailed experimental data, the non-linear regression model produced the best statistical values. However, when the models were

Table 4 Measured and modelled moisture content, difference, % and difference in % units of 14 different covered energy wood piles

Covered stem wood model				
Pile number	Measured moisture	Modelled moisture	Difference between measured and modelled moisture, %	Difference between measured and modelled moisture, units
1	44.68	45.04	–0.36	0.36
2	46.85	43.90	2.94	2.94
3	45.50	48.94	–3.44	3.44
4	53.12	54.28	–1.16	1.16
5	62.07	61.82	0.25	0.25
6	36.60	39.75	–3.16	3.16
7	54.28	50.27	4.01	4.01
8	55.77	55.15	0.62	0.62
9	55.95	55.13	0.82	0.82
10	60.43	57.90	2.54	2.54
11	60.78	60.07	0.70	0.70
12	26.40	32.35	–5.95	5.95
13	47.7	42.64	5.06	5.06
14	50.3	48.76	1.54	1.54
Average	50.03	49.71	0.32	2.33

validated with the imprecise data from real life, the linear regression model gave nearly similar estimations for the moisture content as did observations from the field. For practical use, the linear-regression model was selected, a factor of which is net evaporation.

The models presented can be implemented at every location in Finland, because the Finnish Meteorological Institute has a database for interpolated meteorological observations covering the whole country in a 10 km x 10 km grid. For international use, model parameters needs to be estimated case by case, but it should also be possible to implement the approach worldwide.

Using accurate weather observations for modelling moisture changes in a single place would be preferred, especially from a scientific perspective. However, nowadays the weather observation network is relatively sparse in most countries to represent different areas well. For example, in Finland radiation measurements, which are needed to calculate the evaporation, are only made at a few stations.

Therefore, using gridded data, despite its limitations, is the best option when intended for wide use for the forecast models. With this application, the moisture models, which now use only weather observations and present history, could in the future be relatively easily connected to numerical weather forecast models.

The initial moisture content of wood is important for the accuracy of the estimation. If initial moisture is not measured, there is a risk that it differs from the average table value given in Table 3. The difference will then remain through the storing process and can cause imprecise information of the moisture content.

Winter is a challenging period for the estimation procedure because of the ice and snow. It is difficult to estimate how big a proportion of the snow, for example, ends up in the heating plant and then increases the final moisture value of the pile. In the validation data of this study, there were two piles uncovered (piles 5 and 6), which were stored over the winter, and the difference of the moisture content between the measured and the modelled value is large, i.e. 11% and 14%. This might be due to the snow in the winter season, which has considerably increased the moisture content of the pile.

Data for the forecast models originates from automated monitoring in the spring, summer and autumn, so the daily moisture alteration during winter cannot be estimated by those models. Therefore, this application is recommended to be used from April to October in Finland. It can be assumed that the moisture content of fuel wood increases in the springtime when melted snow penetrates the stacks. When energy wood storages are stored at the roadside over the winter, the calculation has to be stopped during the period from 1 November to 31 March. The calculation starts again on 1 April with moisture content that has been achieved with the model by 31 October. If the storage is uncovered, the moisture content of storage should be increased during the winter period by approximately 5% units.

Measuring the moisture content in different phases of supply chain is challenging. Exact moisture

Table 5 Measured and modelled moisture content, difference, % and difference in % units of 8 different uncovered energy wood piles

Uncovered stem wood model					
Pile number	Age (months from logging)	Measured moisture	Modelled moisture	Difference between measured and modelled moisture, %	Difference between measured and modelled moisture, units
1	2	55.83	57.25	–1.42	1.42
2	4	46.97	53.51	–6.54	6.54
3	7	41.58	42.56	–0.98	0.98
4	9	45.66	48.09	–2.43	2.43
5	12	56.00	41.93	14.07	14.07
6	15	47.20	36.24	10.96	10.96
7	17	40.74	39.23	1.51	1.51
8	21	37.02	32.53	4.49	4.49
Average		46.38	43.92	2.46	5.30

monitoring based on the weight changes of racks, used in this study, is possible only for a limited number of cases. Quality of the real life observations can easily be questioned, because the variation of observations in one truck load is remarkable, and sampling is seldom done according to good scientific principles.

The practitioners of the forest energy business have stated that their requirement of the moisture estimate accuracy for enterprise resource planning purposes would be ±5% of the moisture content. In this study, 77% of observations meet this limit.

5. Conclusions

Modelling is an easy option to make an estimate of the moisture content of an energy wood pile if compared with sampling and measuring the moisture of samples. Models are also a considerably more reliable method for allocation and prioritisation of piles than the »educated guesses« used earlier. In practice, piles are often kept in storage too long »just to be sure« that they are dry enough. This increases storages levels and due to that, the capital costs of supply. In addition, dry matter losses increase due to too long storage times.

Some forest companies have already started to use models as a part of their Enterprise Resource Planning (ERP) systems, and the feedback has been encouraging; models work well enough to give added value. A need for further development is still recognized, especially concerning the varying weather conditions in autumn. Some fuel chip reception stations on heating plants are already using automated continuous moisture metering. If the chain of custody is proof, this information can be used effectively for future development of models.

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Authors' address:

Johanna Routa, PhD.*
e-mail: johanna.routa@luke.fi
Lauri Sikanen, PhD.
e-mail: lauri.sikanen@luke.fi
Natural Resources Institute Finland, Luke
P.O. Box 68, FI-80101 Joensuu
FINLAND

Marja Kolström, PhD.
e-mail: marja.kolstrom@uef.fi
University of Eastern Finland, School of Forest Sciences
P.O. Box 111, FI-80101 Joensuu
FINLAND

Johanna Ruotsalainen, MSc.
e-mail: johanna.ruotsalainen@fmi.fi
Finnish Meteorological Institute, Aviation and Military Services
Yliopistonranta 1 F, 70210 Kuopio
FINLAND

* Corresponding author