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Research paper

Validation of prediction models for estimating the moisture content of logging residues during storage

Johanna Routa [a, *], Marja Kolström [b], Johanna Ruotsalainen [c], Lauri Sikanen [a]

[a] Natural Resources Institute Finland, Luke, P.O. Box 68, FI-80101 Joensuu, Finland
[b] University of Eastern Finland, Mekrijärvi Research Station, Yliopistontie 4, FI-82900 Ilomantsi, Finland
[c] Finnish Meteorological Institute, Aviation and Military Services, Yliopistonranta 1 F, FI-70210 Kuopio, Finland

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ABSTRACT

Increased use of forest biomass for energy and rising transportation costs are forcing biomass suppliers towards better moisture content management in the supply chain. Natural drying is used to decrease moisture content of energy wood. Drying is dependent on wood characteristics and weather conditions. Weather-dependent drying models for estimating the optimal storage time based on average moisture changes in fuel wood stacks stored outdoors have been developed for different stem wood and logging residues. Models are an easy option for estimating the moisture content of energy wood piles compared to sampling and measuring the moisture of samples. In this study, stand and roadside storage models for logging residues were validated against data from field studies and forest companies. Over 200 reference piles for the stand model, 23 piles for the roadside model and 10 piles for the combined model were studied. Results of the validation are promising. The difference between measured and modelled moisture was on average only 0.35%. The presented models can be implemented anywhere in Finland, because the Finnish Meteorological Institute has a weather observation service offering weather history data for every location in Finland. For international use, parameters need to be estimated on a case by case basis, but it should be possible to implement the approach also elsewhere.

1. Introduction

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 its calorific value and from that point of view, the lower the moisture content the better [1,2]. Natural drying is used to decrease the moisture content of energy wood. Usually logging residues are left in the cutting area and spread out to dry. After a drying period the logging residues are forwarded and stored beside the road. Roadside storing time varies according to fuel needs. Energy wood supply operates year round, but the demand is notably higher from October to March [3]. In Finnish energy wood procurement, harvesting of logging residues is very important. In 2014, logging residues comprised 34% (2.6 Mm^3) of the consumption of forest wood chips in Finland [4]. Logging residues are mainly collected from stands dominated by Norway spruce (*Picea abies* L.). In Finland, most of the logging residues are comminuted at the roadside using, for the most part, truck-mounted chippers [5]. The timing of the forwarding of residues is not straightforward. In early-phase forwarding, green residues may heat up, especially in large piles and the dry matter losses are potentially remarkable. Green needles also contain nutrients that are important to the future development of a forest stand. On the other hand, keeping residues on the site postpones site preparation for regeneration in late-phase forwarding. The needles represent approximately 15% of the logging residues from Norway spruce [6]. Nurmi and Hillebrandt [7] reported a reduction in needle content from 19.1 to 4% during one month of spring storage.

After tree cutting, wood starts to interact with the surrounding microclimate [8]. In Nordic conditions, the moisture content of wood drops rapidly in the spring because of the low relative humidity of air. In late August and September, evaporation rate usually decreases and the moisture content of the wood increases, in some cases even above the “original” moisture content after cutting. Maximizing natural drying and minimizing re-moistening are key

* Corresponding author.
E-mail addresses: johanna.routa@luke.fi (J. Routa), marja.kolstrom@uef.fi (M. Kolström), johanna.ruotsalainen@fmi.fi (J. Ruotsalainen), lauri.sikanen@luke.fi (L. Sikanen).

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elements in the quality assessment of energy wood [9]. The timing of the operations in relation to seasons is crucial in order to maximize the quality and monetary value of the energy wood.

The latest methodology for monitoring moisture change has been constant weighing of piles in racks built on load cells [10,11]. This methodology allows moisture changes to be monitored in much more detail than with previous sampling methods. The method also gives the moisture value of the whole pile, which is challenging to determine using sampling methods [12]. Weight can be recorded automatically and as often as needed, which enables exact investigation of the effect of weather on energy wood storage and its moisture content.

Constant weight monitoring shows the drying and moistening of the biomass, but the monitoring can be disturbed by dry matter losses. The weight change is the sum of the water to be added or removed and the dry matter (mainly) removed from the pile by microbiological processes [8]. Dry matter losses can be caused either by microbial activity, most commonly fungal attacks (biological), or spillage of material during handling and storage (technical) [13].

The first ideas about using models to predict moisture content of wood were presented in the 1980's. Stokes et al. [2] published their models for soft and hardwoods in southeastern USA. Liang et al. [14], Gigler et al. [15], Filbakk et al. [16] Murphy et al. [17], Erber et al. [10], Dong-Wook and Murphy [18] and Routa et al. [19] have developed different drying models for different species. All approaches in fuel wood moisture content modeling have one common target variable: moisture content, or rather the moisture content alteration during a specified period. The alteration can be explained by a large variety of explanatory variables, like meteorological variables, parameters of storing, material type and duration of storage.

The objective of this study was to develop a model to estimate the moisture content of logging residues during storage. The prediction models are necessary to support operational planning in energy wood supply. Changes of moisture content in response to weather conditions were connected. The requirements of the model were: easy application to the operational planning systems, simple and quick to calculate. The developed models were validated against data from other studies and forest companies.

2. Material and methods

2.1. Experimental design

At the Mekrijärvi Research Station of the University of Eastern Finland (62°46′N, 30°59′E), eight drying racks with continuous measuring systems were built to study roadside storage (Fig. 1). The purpose of the racks is to simulate energy wood storage beside the road in the forest after cutting. The drying racks are metal frames measuring 2.5 m in width by 2.8 m in height and 2.6 m in length. The racks are similar to those used on timber trucks to carry logs. In the system, four load cells in each corner of the rack continuously measure the weight of one pile (Fig. 2). These four cells are connected to a junction box, which is connected onwards to a weighing transmitter. The system enables continuous monitoring of pile weight. Weight data is stored in a file and changes in weight can be followed via the Internet. 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 there is more weight, the material has higher moisture content. The material in the rack was piled by a machine. As the piles in the racks are quite small compared with actual storage in the field, there are cover papers on the bottom and sides of the racks. The paper decreases the edge effect of the pile, preventing too fast drying. The piles are designed to replicate parts of larger roadside piles created during real harvesting operations.

Fig. 1. One of the drying racks at the University of Eastern Finland's Mekrijärvi Research Station.

In addition, two special drying platforms were built in 2013 (Fig. 3) for emulating drying in a small logging residue pile in stand conditions. The data for the stand model for logging residues was collected from platforms in summer and autumn 2013, 2014 and 2015, and from a field experiment 2012.

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^{-1}), wind direction (°), solar radiation (W m^{-2}) and rainfall (mm), air pressure (hPa), ground temperature (°C), rainfall intensity (mm h^{-1}), 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 all of Finland. This data set consists of weather observations (e.g. temperature, humidity, precipitation), which have been interpolated to a 10 km × 10 km grid using the Kriging interpolation method [20].

The storage area at the Research Station is an open area, next to a lake and its elevation is 155 m above sea level. Mean annual precipitation in this area is 668 mm and mean annual temperature 2.1 °C. The mean temperature for the drying season is 9.8 °C [21]. The long-term average of precipitation for the drying period is 439 mm. The long-term averages (1971–2000) were taken from the nearby station, Ilomantsi Kirkonkylä, because there was no data from the Mekrijärvi station, as it was founded in 1999. The Ilomantsi Kirkonkylä station is located 11.6 km from Mekrijärvi and therefore represents the same climate conditions. The mean snow depth in the Mekrijärvi area is approx. 45–65 cm in the winter months.

As shown in Table 1, the first drying season (2012) was not optimal for wood drying. The mean temperature was slightly lower than the long-term average mean temperature and the precipitation sum was almost 50% more than the long-term average [21]. The best drying season was in 2013 when the mean temperature was highest and the precipitation sum was smallest. In 2014 and 2015 conditions were similar to the long-term average.

Fig. 2. Load cells in every corner of the rack.

Fig. 3. Special drying platforms for simulating drying in a small logging residue pile in stand conditions.

Table 1
The mean temperature and precipitation sum from April to October and long-term average (1971–2000) for these seven months.

	2012	2013	2014	2015	Average 1971–2000
Average mean temperature	9.5 °C	10.8 °C	10.0 °C	9.7 °C	9.8 °C
Precipitation sum	605,3 mm	399,4 mm	445,2 mm	442 mm	439 mm

2.2. Sampling method

When piling up the logging residues, 3–4 samples of each roadside pile were taken randomly from different levels (top, middle and bottom) of the pile. The samples, mostly branches and some stem pieces were chipped with a gardening chipper. The logging residues of platforms were fresh, so it was assumed that the moisture content of the material was quite homogenous and that is why only one sample per pile was analyzed. The moisture content (wet basis) was determined with the oven-dry method. The sampling method closely followed the solid biofuel standard EN 14774.

It was assumed that moisture content varies within the pile after the storage period. When the piles were unloaded the material from each pile was chipped with a large drum chipper. Samples were taken from chips originating from the top, middle and bottom of the pile. All samples were analyzed with the oven-dry method.

2.3. Validation data

The validation data has been collected from the studies implemented in field conditions. We gathered the data of all cases in which enough information was available. The key information was the measurements of moisture content of logging residues after different logging operations. In addition, the variation of the drying events is large in field conditions and the validation of the models requires as extensive data as possible.

The validation data 1 of the stand model, consisting of 159 test piles of Norway spruce logging residues, was measured in 8 different locations. The validation data was collected in Central Finland during summer 2012. Moisture samples were taken at the beginning of the experiment from each pile. The samples, mostly branches and some stem pieces were chipped with a gardening chipper. Branches were collected from the upper part of the pile, and inside the pile. Chips were mixed and two samples per pile were taken for analysis of moisture content. The moisture content (wet basis) was determined using the oven-dry method. The sampling method closely followed the solid biofuel standard EN 14774. At the same time all stand piles were weighed. The piles were transferred to the filter fabric just after logging, and as the fabric held the wood in a type of sling, it could be used to help record the weight of the wood using the forwarder's scale. The average weight of the piles was 873 kg. The storage time was around 30 days, except one pile was stored 65 days. At the end of the experiment the piles were weighed again with the same method and the moisture content of a pile was determined by weight change and initial moisture content.

The validation data 2 of the stand model, consisting of spruce logging residues in 12 different locations and logging residues of (*Pinus contorta* Douglas ex Loudon) in one location, was collected from Eastern Finland in 2009. Moisture samples were taken from forwarder loads. Branches were collected from the upper part of the load, inside the load and the bottom of the load with a grapple load. The samples, mostly branches and some pieces of stem, were chipped with a gardening chipper. Chips were mixed and three samples per load were taken for analysis of moisture content, in total 178 samples.

In addition, five logging residue piles were taken from same data set used for validation of the roadside model (validation data 1) and one pile from a field experiment from Mekrijärvi in Eastern Finland. The moisture samples were taken from piled chips in the first cases and with a gardening chipper in the Mekrijärvi experiment.

The validation data 1 for the roadside model was collected from Central Finland in 2012. In total 13 cases was studied including both covered (4) and uncovered (9) piles. The weather data was taken from the nearest grid based on the coordinates of the logging site. The energy wood was driven to the Mäntän Energia power plant and chipped there. The moisture samples were taken from piled chips; 6–8 samples were taken with ladle sampling and added 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 L). The plastic bags were delivered immediately to the laboratory, where the moisture content was measured using the oven-dry method.

The validation data 2 for the roadside model was collected in Central Finland in 2011. The sampled piles (10 piles) were selected so that they present average energy wood storage piles typical of the wood energy industry in Finland. All the roadside storage piles were covered with Walki cover paper after forwarding. 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 and added 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 L). The plastic bags were delivered immediately to the laboratory, where the moisture content was measured using the oven-dry method.

In addition, we tested to use both models together. We started to use stand model just after cutting, and as soon as energy wood has been forwarder, we start to use roadside models. We call this combined model in the results section. The validation data for the combined stand & roadside model was the same as roadside model data 2.

2.4. Data analysis

The data from continuous measurements was prepared for the analysis. The running mean of the weight, the moisture content and the daily moisture change for each day was calculated. The data from the 1st of April to the end of October was used, and the winter months were excluded because of disturbing snow cover within the weight data. The Finnish Meteorological Institute calculated the evaporation from the gridded data, according to the universal standard of the FAO Penman-Monteith method [22] additional weather parameters (precipitation P (mm), volumetric moisture of the surface layer, W_{vol} (m^3 m^{-3})) were taken from the grid data. The interpolation method is explained in detail in Venäläinen and Heikinheimo [20], 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 modeling approaches were tested to estimate daily change of moisture content such as the linear regression model, multiple linear regression model and non-linear models. The following were used as determining variables: temperature, precipitation, evaporation, wind speed and humidity. However, the best variable was net evaporation, which explains the difference between evaporation and precipitation. In fact, this variable contains all the most important weather parameters affecting energy wood drying. For the model form we chose the simplest regression model with one determining variable in the case of roadside models.

The stand model was the trickiest one, since in stand conditions drying and remoistening are fast processes and conditions in the stand strongly affect these variables. Small piles can dry very fast in suitable conditions, but on the other hand also remoisten very fast. In modeling it is not very easy to take all affecting factors into consideration. In our model we predict drying during the whole period in a stand. As a determining variable we use the sum of precipitation ratio for the sum of evaporation during the drying period in a stand. Calculating the sum begins when the surface layer of the ground starts to dry in spring. In winter, when the ground is frozen and there is snow in the ground, the moisture content of energy wood is not decreasing. We found that meteorological parameter volumetric moisture content of surface layer, W_{vol}(m^3 m^{-3}) could be used as an estimate when not only the ground but also the energy wood starts to dry. Therefore drying (and calculating the sum) starts when W_{vol} (m^3 m^{-3}) at the grid point in question reaches values below 0.5. Calculating W_{vol} (m^3 m^{-3}) is explained in Vajda et al. [23]. Typically, the ground surface starts to dry between March and May in Finland depending on the location or the seasonal variation in weather. In autumn the end of drying season varies less. Drying of ground ends typically in October or November.

Data for those models originates from automated monitoring in the spring, summer and fall, so the moisture alteration during winter cannot be estimated by those models because of snow weight during winter. Therefore this application is recommended to be used for March to October depending on the above mentioned volumetric surface moisture content change. It can be assumed that the moisture content of fuel wood increases in springtime when melting snow penetrates the stacks. The target variable is the moisture content alteration per day in % on the wet basis (DMC = daily moisture change). The analyses were performed with IBM SPSS Statistics version 22.

2.5. Validation

To verify fuel wood drying models, reference piles are one possible option. Samples must be taken from the piles, which should consist of similar materials in assortment and tree species. Moisture content estimation is done using the model gained from the rack experiment. The result is compared to the reference pile moisture content.

Validation data has not been used in any form for actual modeling. The developed models are applied to the cases of the validation data. To assess how the model value meets the measured value, we used the limit of ±5%. The limit is based on discussions with the users of the model, i.e. companies who supply energy wood to power plants. The accuracy of ±5% is acceptable in a normal energy wood supply chain.

The weather data was taken from the nearest grid based on the coordinates of the logging site. The results of the models are compared to the measured moisture content of the cases of validation data.

A Mann-Whitney test was used to compare the difference between measured and modelled moisture contents with IBM SPSS Statistics version 22, using the critical level at $p < 0.05$. The Mann-Whitney test is considered to be one of the most powerful nonparametric tests, especially testing differences in the location of the distribution [24].

3. Results

3.1. Result of modeling

Stand models and roadside storage models for logging residues were developed (Table 2). Use of the models starts with determining the moisture content of fresh wood. For that reason, average moisture of fresh logging residues (spruce and pine), depending of the cutting month, is presented in Table 3 [7,25–31].

Using the models requires applying some restrictions, since the moisture content should not exceed the moisture content of 60% and it should not be under 25%, because it is not realistic that moisture content of logging residues goes under that value. If logging residues have been logged during winter, the moisture content of logging residues starts at 60% in the beginning of the drying season. The drying season begins in spring when the snow has melted and the ground surface starts to dry (the surface moisture content reaches a value below 0.5.)

3.2. Stand model

The stand model of logging residues was tested against data from field studies. The difference between measured and modelled moisture content was on average 1.09% (Table 4). The difference within measured and modelled moisture content was on average 3.2% units. Moisture estimate accuracy was between the ±5% limit in 81% of observations. Difference between the measured and modelled value was not statistically significant ($p = 0.647$). The variations in model predictions between measured and modelled moisture did not depend on storage time; there were variations with short and long storing times.

3.3. Logging residues roadside storage model

The difference between measured and modelled moisture content varied a lot, but on average it was only 0.2%. The difference in percent units was on average 4.57 (Table 5). The validation included data for both covered and uncovered piles. Modelled values both under- and overestimated the measured results. However, 78% of observations were within the ±5% limit. Difference between measured and modelled values was not statistically significant ($p = 0.767$). In general, the model for covered piles was more accurate; 85% of predictions met the ±5% limit. With uncovered piles 67% met the ±5% limit. The variations in model predictions of moisture did not depend on the storage time, there were variations with short and long storing times.

3.4. Combined stand & roadside model

Logging was done during the winter and logging residues were forwarded in spring. Use of the stand model was started in April when the moisture content of the surface layer is less than 0.5. The roadside model was utilized after forwarding. In the cases when logging was done during the winter and logging residues have been under snow cover, we started from a moisture content of 60% in April. The difference between measured and modelled moisture content was on average 1.3%. The difference in percent units was on average 3.5 units (Table 6). 80% of observations were between the ±5% limit Difference between measured and modelled values was not statistically significant ($p = 0.579$). In this data, the storing time

Table 2
Drying models for logging residues on stand and covered and uncovered logging residues stored on a roadside.

Stand model				
Drying, during the period % = *coef* ∑ precipitation / ∑ evaporation + const*				
The sum of precipitation or evaporation is calculated from the logging date until the end of the storage period. The ration of the sums may not exceed the value of 1.5.				
Moisture content (i) = moisture content in logging − Drying				
Model	coef	const	R^2	SE
Logging residues	−16.397	20.64	0.73	7.9
Roadside storage models				
Daily Moisture Change (DMC) = coef* (evaporation − precipitation) + const				
Moisture content (i) = moisture content (i-1) - DMC				
Model	coef	const	R^2	SE
Logging residues, covered	0.105	−0.072	0.44	0.36
Logging residues, uncovered	0.17	−0.076	0.64	0.57

Table 3
Moisture content of fresh logging residues depending on the cutting month in Finland.

	Moisture content of fresh logging residues, monthly, %											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pine	55	55	55	54	54	54	54	53	54	54	55	54
Spruce	52	52	51	51	51	50	51	51	51	50	51	52

Table 4
Measured and modelled moisture content, difference, %, and difference in % units of different stand model piles. Mean values are bolded.

Stand model				
Site id	Measured moisture, %	Modelled moisture, %	Difference between measured and modelled moisture, %	Difference between measured and modelled moisture, units
1001	36.49	32.96	3.52	3.52
1002	51.68	46.11	5.56	5.56
1003	39.47	34.72	4.75	4.75
1004	41.48	34.62	6.86	6.86
1005	32.30	31.13	1.17	1.17
1006	39.41	40.49	−1.08	1.08
1007	35.74	33.24	2.51	2.51
1008	49.46	41.07	8.39	8.39
1009	42.91	41.52	1.39	1.39
1010	44.00	43.60	0.40	0.40
1011	43.45	41.53	1.92	1.92
1012	44.19	41.53	2.66	2.66
1013	38.44	41.77	−3.33	3.33
1014	38.78	41.70	−2.92	2.92
1015	44.60	42.87	1.73	1.73
1016	40.32	43.98	−3.66	3.66
1017	46.91	43.60	3.31	3.31
1018	31.01	35.78	−4.77	4.77
1019	37.66	46.97	−9.31	9.31
1020	39.87	38.97	0.90	0.90
1021	45.56	43.30	2.27	2.27
1022	41.50	34.75	6.75	6.75
1023	55.80	55.76	0.04	0.04
1024	39.40	40.52	−1.12	1.12
1025	35.60	33.16	2.44	2.44
1026	38.34	36.50	1.84	1.84
1027	32.00	34.77	−2.77	2.77
Mean	**40.98**	**39.89**	**1.09**	**3.24**
Min	31.01	31.13		0.04
Median	39.87	41.07		2.66
Max	55.80	55.76		9.31

Table 5
Measured and modelled moisture content, difference, %, and difference in % units of different roadside piles. Mean values are bolded.

Pile id	Measured moisture, %	Modelled moisture, %	Difference between measured and modelled moisture, %	Difference between measured and modelled moisture, units
2001	46.60	57.97	−11.37	11.37
2002	41.60	60.00	−18.40	18.40
2003	48.70	43.80	4.90	4.90
2004	48.70	38.61	10.09	10.09
2005	43.50	40.67	2.83	2.83
2006	53.90	49.64	4.26	4.26
2007	47.10	43.07	4.03	4.03
2008	46.80	42.93	3.87	3.87
2009	44.80	42.93	1.87	1.87
2010	52.00	51.85	0.15	0.15
2011	54.20	49.94	4.26	4.26
2012	49.40	45.60	3.80	3.80
2013	47.30	45.61	1.69	1.69
2014	31.85	36.64	−4.79	4.79
2015	33.79	34.88	−1.09	1.09
2016	29.03	28.73	0.29	0.29
2017	39.96	42.76	−2.80	2.80
2018	32.42	39.12	−6.70	6.70
2019	34.99	31.05	3.94	3.94
2020	39.57	40.39	−0.82	0.82
2021	31.78	36.07	−4.29	4.29
2022	28.34	25.0	3.34	3.34
2023	30.59	25.0	5.58	5.59
Mean	**41.61**	**41.40**	**0.20**	**4.57**
Min	28.34	25.00		0.15
Median	43.50	42.76		3.94
Max	54.20	60.00		18.40

was between 107 and 136 days. All the models could predict the moisture content of logging residues well, and using stand model and roadside model together as combined model gives the best results (Fig. 4).

4. Discussion

In general, the difference between modelled and measured data was small on average, but there were large variations in the

Table 6
Measured and modelled moisture content, difference, %, and difference in % units of different stand model piles of combined stand & roadside model. Mean values are bolded.

Pile id	Measured moisture, %	Modelled moisture, %	Difference between measured and modelled moisture, %	Difference between measured and modelled moisture, units
28	31.85	34.59	−2.74	2.74
29	33.79	29.18	4.60	4.60
30	29.03	27.97	1.06	1.06
31	39.96	39.26	0.70	0.70
32	32.42	32.65	−0.22	0.22
33	34.99	36.70	−1.71	1.71
34	39.57	40.30	−0.73	0.73
35	31.78	24.14	7.63	7.63
36	28.34	26.93	1.41	1.41
37	30.59	22.81	7.78	7.78
Mean	**33.23**	**31.45**	**1.78**	**2.86**
Min	28.34	22.81		0.22
Median	32.14	30.92		1.56
Max	39.96	40.30		7.78

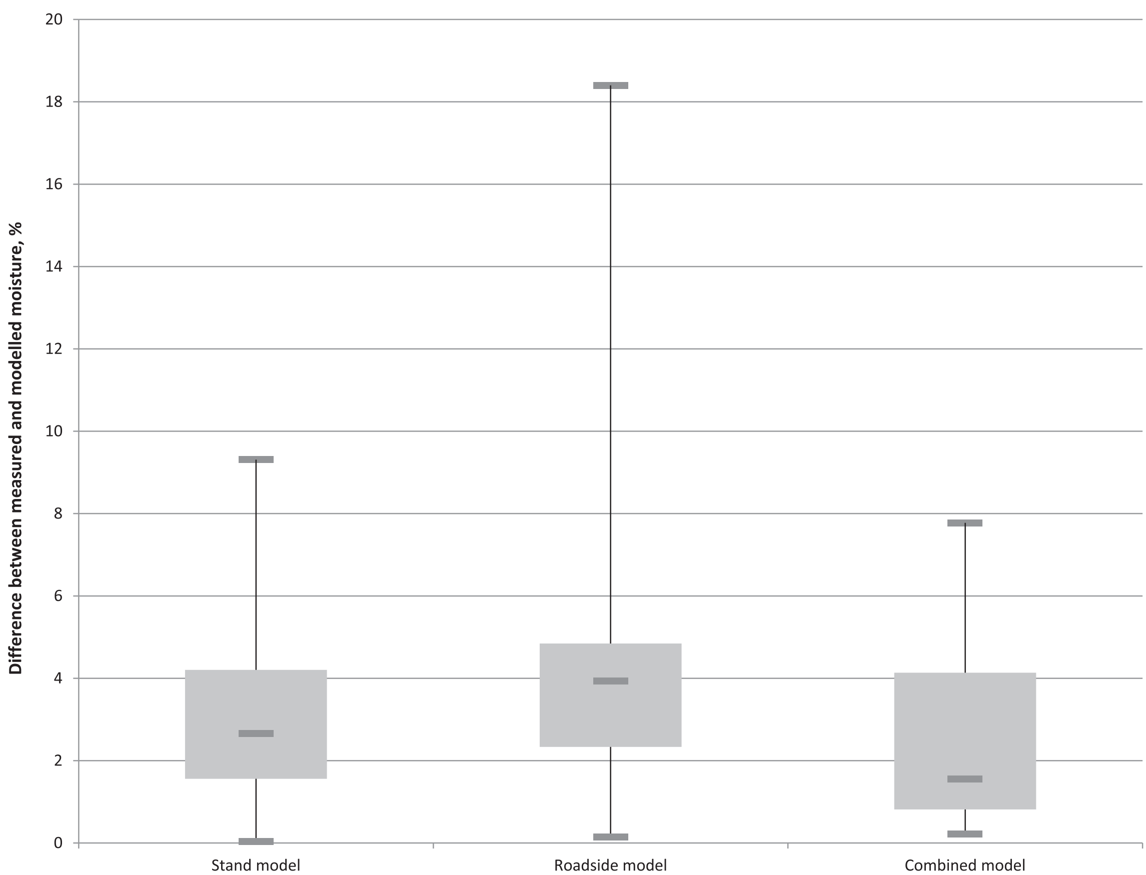

Fig. 4. Difference of measured and modelled moisture content of stand piles, roadside piles and combined piles of logging residues.

validation data. The models presented in this article can be implemented at every location in Finland thanks to the gridded weather data for the whole country provided by the Finnish Meteorological Institute. This data set consists of weather measurements (e.g. temperature, humidity, precipitation), which have been interpolated to a 10 km × 10 km grid by the Kriging interpolation method [20]. This data can be used for storage locations where recorded weather data is not available and by using the moisture content models it is possible to obtain moisture content estimations of any pile anywhere. For international use, model parameters need to be estimated on a by case by case basis.

Modeling logging residue moisture content is challenging. The variation between logging residue piles is huge, and even inside the pile the moisture content can vary greatly. Logging residues are heterogeneous material, and weather conditions, storage conditions and microclimate of the storage location all have remarkable effects on drying. Reasons for the substantial differences between predictions and measured values could be, for example, the microclimate of the site, the moisture content measurement errors and weather data inaccuracy.

The initial moisture content of wood is important for the accuracy 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 it can lead to imprecise moisture content information. Another challenge is sampling; measuring the moisture content at different phases of the supply chain is difficult. Quality of actual observations varies, and even within the same pile the moisture varied greatly [8,16,19]. Dry matter losses in logging residue piles could be remarkable, and this also affects moisture measurements [8,16]. Therefore, more research should be done in order to provide more accurate data on dry matter changes of energy wood during seasoning. It is not recommended to store logging residues in the forest stand or at the roadside storage location for too long, because the dry matter losses are so high that economic profitability suffers. In addition, in Nordic conditions, in the winter period, it is hard to estimate moisture contents because of the snow and ice. Estimating the amount of snow in a logging residue pile and the amount ending up at the power plant with residues is hard, and this requires further research.

Data for the estimating 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, use of this application is recommended from March to October in Finland, depending on the weather data. Calculation begins when the surface layer starts to dry and $W_{vol}(m^3\ m^{-3})$ at the grid point in question yields values below 0.5 and calculation ends when $W_{vol}(m^3\ m^{-3})$ remains permanently at its maximum value of 0.5. Typically, the surface starts to dry between March and May in Finland and drying ends in October or November, depending on location and seasonal variation in weather. It can be assumed that the moisture content of fuel wood increases in the springtime when melted snow penetrates the stacks. If the storage pile is uncovered, it is suggested that the moisture content of the storage pile is increased during the winter period by approximately 5% units. Restrictions must be set for this logging residue model: if the estimated moisture content is over 60% or under 25%, the use of the model has to be suspended. For example, in typical stand conditions, if logging residues have been logged during the winter (November–February), the moisture content of logging residues starts from 60% in the beginning of drying season regardless of logging month.

Utilizing gridded weather data in modeling enables using models at every location in Finland, and there is no need to use actual site-depended weather observations. Disadvantages of this method are that it cannot take into consideration any microclimate effects that influence drying. If drying conditions are very specific, this model cannot predict moisture content. For that reason, we have been developing the site categorization and some instructions for selecting optimal drying places [32].

The stand model for logging residues works very well with this validation data, but obviously needs further development. The model is based on the relation of precipitation sum and evaporation sum, and if the period is very dry (high evaporation and no precipitation) the model predict same drying for very short or very long period.

In the case of the combined stand and roadside storage model validation, the situation is similar to the real life situation, because we do not have any moisture content measurements when we start to utilize the model. The practitioners of the forest energy business have stated that their requirement for moisture estimate accuracy for enterprise resource planning purposes would be ±5% of the moisture content. In this study, 80% of moisture estimates meet this limit.

5. Conclusions

In this study, drying models for logging residues in a forest stand and covered and uncovered logging residues stored on the roadside have been introduced and validated. The performance of these models was good even though there can be some inaccuracy in the results due to specific storage conditions or the lack of measurements of initial moisture content. Using moisture prediction models is an easy and cheap way to improve biomass fuel quality but also reduce transport costs and CO_2-emissions. The accuracy of the developed models is sufficient to offer substantial improvement for planning and scheduling biomass supply and for resource allocation of chipping and harvesting companies. The models are applicable all over the country and they are also relatively easy to include in forest companies' information systems.

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