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THE IMPORTANCE OF ACCURATE MEASUREMENT OF COMMINUTED LOGGING RESIDUES' MOISTURE CONTENTS FOR SMALL-SCALE FOREST OWNERS

Bioenergy from logging residues is an important contributor to Swedish energy supplies. Thus, accurate measurements of delivered logging residues' energy contents are very important for both sellers and buyers. Deliveries' energy contents are highly correlated with their moisture contents, and thus are determined in southern Sweden (and elsewhere) by measuring their masses and moisture contents. There is insufficient knowledge, however, about the variation in moisture content within and between deliveries, and hence the minimum number of samples needed to obtain the required precision. Thus, these variations were examined in detail in the presented study. Nested analysis of the variance of the acquired data shows that at least nine samples are required to obtain estimates of a delivery's moisture content with a 3% margin of error. For high volume trade, such as that between forest companies and the energy-conversion industry, current measurement practices are sufficiently accurate. For private forest owners making single deliveries, however, higher precision is required as inaccurate measurements can strongly affect prices.

Keywords: forest residues, bioenergy, forest-fuel, scaling, moisture content, private forest owners

Introduction

Bioenergy is an important component of Swedish energy supplies, providing about 129 TWh of the total 565 TWh supply in 2013 [Swedish Energy Agency 2015]. Logging residues currently contribute about eight TWh per year [de Jong et al. 2012], and could potentially contribute roughly twice as much [Routa et al. 2013]. These residues, defined as the unmerchantable above ground biomass left behind in clear-cuts after roundwood harvests, consist of branches, tops and small trees [Hakkila 1989]. They may be left in the forest, or gathered to highly

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varying extents depending on the region, their composition and possible uses. In Sweden, logging residues gathered from clear-cutting sites for energy production are dominated by Norway spruce (*Picea abies* (L.) Karst) and some Scots pine (*Pinus sylvestris* L.) [Routa et al. 2013].

Logging residues can be procured for energy production by several systems. The logging residues are placed in small heaps by the harvester during so-called fuel-adapted logging operations. They are either left to dry in the heaps for a summer, then forwarded and stored in larger roadside windrows until required at the designated energy-conversion site, or delivered to terminals for storage during periods when fuel requirements are low. At an appropriate time the logging residues are comminuted and delivered. In southern Sweden the most common being chipping at landings. The majority (approximately two thirds) of the harvested volume is usually comminuted by a forwarder-mounted chipper, which transfers the chips produced into containers, either by tipping or blowing [Routa et al. 2013].The containers are then transported, usually in batches of three per delivery, by switch-body container trucks [Thorsén et al. 2011].

The quality of logging residues as fuels varies substantially, and one of the most important factors for assessing their quality is their moisture content since it influences many other quality parameters (e.g. net calorific value), and its suitability to be stored [Thörnqvist 1985; Nylinder and Törnmarck 1986; Jirjis 1995; Suadicani and Gamborg 1999; Pettersson and Nordfjell 2007; Filbakk et al. 2011]**.** According to Hakkila [1989], the moisture content of freshly harvested logging residues is around 50 percent. Numerous studies [Thörnqvist 1985; Jirjis and Lehtikangas 1993; Nurmi 1999; Nurmi and Hillebrand 2001; Gautam et.al 2012; Nilsson et al. 2013, 2015] have shown that drying uncomminuted forest fuels in piles significantly lowers the moisture content. Thus, the moisture content of residues at comminution and delivery is often beyond the control of the forest owner, but the forest company can decide the timings of placement in windrows at landings and comminution. The most important factors for good drying are exposure to wind and sun, but also covering the windrows [Kofman and Kent 2009]. The drying conditions can therefore be governed to some extent by the forest company. Drying has been shown to be economically beneficial, for example Erber et al. [2012] found that air-drying increased the prices of pine logs for energy use by 14.40 € per ton, relative to prices for similar, freshly harvested logs.

The residues' moisture contents are usually determined at the energy--conversion sites by oven-drying randomly selected samples of delivered fuel chips. In Sweden, the samples are usually acquired by someone standing on a measuring bridge and collecting one to two litre samples from twenty to fifty centimetre depths at three places in a consignment. The samples are then usually mixed, oven-dried and weighed to determine the consignment's moisture content. Oven-drying is generally used since it is a widely accepted and well--established method that does not demand any special laboratory equipment

[EN ISO 18134-2:2015]. Furthermore, it is highly accurate, providing standard deviations of one percent or less [Samuelsson et al. 2006; BioNorm II 2011]. Some energy-conversion industries acquire samples after unloading, in order to obtain more accurate measurements. From the moisture content, the net calorific value per unit dry mass (DM), $q_{v,net,d}$, is calculated using predefined formulas for different fuels with well-defined constants. The mass of the fuel chips is usually determined using accurate fixed scales at the energy-conversion site or terminal. The mass, together with a measurement of the moisture content, provides an accurate way of determining the total energy content in a delivery [Nurmi 1992].

The precision of the scaling of logging residues has been regulated since March 1st 2015 [Swedish Statutes 2014], but no Swedish regulations covered the scaling of chipped forest fuels before then. Björklund and Eriksson [2013] calculated that to reach these precision requirements with 95% certainty for scaling chipped logging residues, at least six samples for each delivery would be required. Nylinder and Törnmarck [1986] recommended taking five samples for each delivery. These studies also show that larger volumes of deliveries decreases the amount of samples needed to reach sufficient precision. According to the new regulations a delivery of chipped logging residues with a dry mass of up to twenty-five tons is allowed to deviate with a maximum of eighteen percent of the dry mass and twenty percent of the total energy content in MWh Swedish Forestry Agency [2014].

The aims of this study were to evaluate the accuracy of current moisture content measurements in the energy-conversion industry, and determine the dependency of prices of consignments on this accuracy, particularly for small--scale forest owners.

Material and methods

The material considered in this study consisted of forty four deliveries of comminuted logging residues, collected from within 100 km of Växjö, Kalmar, and Trollhättan in southern Sweden (56.53, 56.40 and 58.29°N, respectively; fig. 1). Each was delivered in a set of three containers, except one which was delivered in two containers (with corresponding adjustments in the calculations). Twenty-nine were collected in winter, between January and early April 2012: ten each from Växjö and Kalmar, and nine from Trollhättan. The other fifteen consisted of five deliveries from Kalmar and ten from Växjö, gathered in summer (May and June 2012). In each case the logging residues were gathered from clear-felled stands with the following average distribution of tree species: sixty five percent Norway spruce, thirty percent Scots pine and five percent road-leaves, mainly birch (*Betula* spp.). It should be noted that this distribution is not proportional to the distribution of logging residues, the volumes of which differ from distributions of harvested stem volumes [Hakkila 1989].

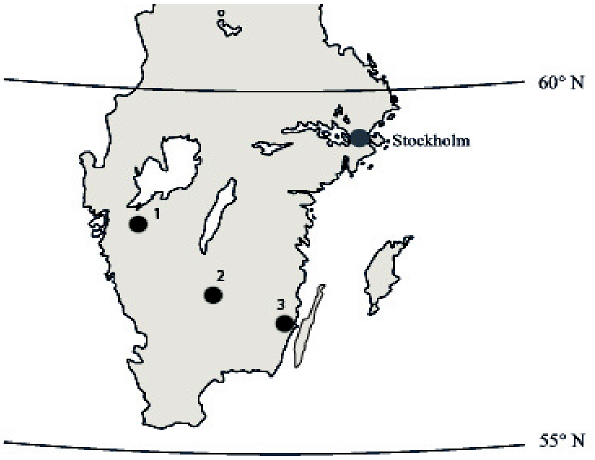

Fig. 1. A map of southern Sweden showing the three locations where the logging residues were gathered, within 100 km of Trollhättan (1) Växjö (2) and Kalmar (3)

When delivered to the energy-conversion industrial sites, representatives of the Timber Measurement Association of South Sweden measured the moisture content (MC_2) of consignments by the standard method described above. In addition, ten samples were collected from the stationary stockpile obtained from unloading each container of material from the Kalmar and Växjö sites, following the standard method EN 14778:2011 to determine a reference moisture content (MC_1). Deliveries to Trollhättan, however, were unloaded directly into a fuel depot, so the reference samples were acquired by collecting fuel chips in buckets during unloading. In each case the reference moisture content was then determined by oven-drying according to the standard method EN ISO 18134-2: 2015, and the net calorific value per unit of dry mass was calculated using the following simplified equation.

$$q_{v,net,d} = \left(\left(q_{v,gr,d} - 2.45 \times 8.94 \times \frac{H}{100} \times \left(1 - \frac{A}{100} \right) \right) - \left(2.45 \times \frac{MC}{100 - MC} \right) \right) \tag{1}$$

Here: $q_{v,net,d}$ is the net calorific value at constant volume in MJ·kg^{-1} DM, $q_{v,gr,d}$ is the gross calorific value at constant volume (approximated to 20.8 MJ·kg^{-1} DM), 2.45 is the latent heat of vaporization of water at 20ºC in MJ·kg^{-1}, 8.94 is the number of water-parts formed by one part hydrogen in the fuel, H is the hydrogen content of oven-dry fuel (approximated to six percent [EN 14918:2010]), A is the contaminating ash content (approximated to two percent) and MC is the moisture content of the comminuted logging residues.

As the summer and winter deliveries significantly differed, the data were modelled using a nested Analysis of Variance [Sahai and Ojeda 2005;

Montgomery 2009], treating seasons as a fixed main factor and the moisture content as a random factor nested within each season. More explicitly,

$$y_{ijk} = \mu + \tau_i + \beta_{j(i)} + \varepsilon_{(ij)k} \tag{2}$$

where y_{ijk} is the observed moisture content (MC) k during season i (1 for winter, 2 for summer) of delivery j, μ is the overall theoretical mean of the moisture content, τ_i is a fixed effect for the season, $\beta_{j(i)}$ is a random effect of the moisture content on a delivery within a season with $j(1) = 1, \ldots, 29$ and $j(2) = 1, \ldots, 15$ referring to the number of deliveries in the winter and summer season, respectively, and $\varepsilon_{(ij)k}$ is the residual error.

For each delivery there are thirty observations, except for one delivery in the summer season, for which there are twenty observations, so $k = 1, \ldots, 30$ for each i and j except for the anomalous delivery in the summer season (for which $k = 1, \ldots, 20$). The $\beta_{j(i)}$ and $\varepsilon_{(ij)k}$ variables are assumed to be independent, not necessarily normally distributed, with zero means and variances s_β^2 and σ_ε^2 respectively. The variance σ_β^2 is interpreted as the variance between deliveries and σ_ε^2 the variance within a single delivery. The nested analysis of variance was implemented using the IBM software SPSS (www.ibm.com), with the UNIANOVA command with Type I sum of squares from which estimates σ_β^2 and s_ε^2 of σ_β^2 and σ_ε^2 were obtained. The same nested analysis of variance approach was used to analyze the variation in the residues' net calorific value per unit DM.

The number of samples required to determine the moisture content with given precision (three, five, seven and nine percent, at a ninety five percent confidence level) was calculated from the standard deviation of the moisture measurements within an arbitrary delivery (s_ε). From s_ε and the standard deviation between deliveries (s_β), the impact of moisture content measurements was evaluated at a ninety five percent confidence level for each of three sampling scenarios (taking thirty, three or no samples from each of one, ten or a hundred deliveries). The calculated confidence level was then used to evaluate the number of moisture content samples needed to obtain a given margin of error. In more detail, the number of samples used to estimate moisture contents were: thirty per delivery, giving the reference (MC_1) values; three samples per delivery, as in standard current practices of the energy conversion industries, giving the MC_2 values; and standard values of the net calorific value, based on past experience (calculated here as the mean for all forty four deliveries), rather than measurements of consignments.

Results and discussion

A comparison of the mean moisture content values, using a box and whisker plot, showed that most of the MC_2 measurements are close to the corresponding MC_1 values. More precisely, roughly two-thirds of the MC_2 measurements are within ± three percent of the MC_1 measurements (fig. 2). There are, however, two clear outliers (deviating by –16.3 percent and 20.2 percent; more than three times the interquartile range from the mean of the reference measurements) and one deviating by minus nine percent (more than 1.5 times the interquartile range). The sole deviation of more than twenty percent was obtained for one consignment of a series of five from a particular clear felling, delivered during the summer. While MC_1 and MC_2 values were around sixteen percent for the other four deliveries, and the MC_1 value for the fifth delivery was also sixteen percent, its MC_2 value was thirty six percent. A possible explanation for this discrepancy is that heavy rain during transport of the anomalous delivery strongly affected MC_2 samples taken from the top of the container before the fuel chips were unloaded.

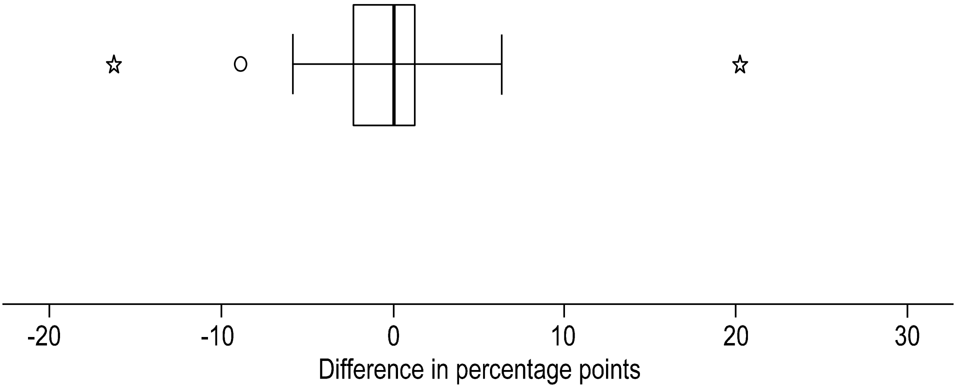

Fig. 2. Differences in percentage points between the reference moisture content (MC_1) and the moisture content determined by personnel at the energy-conversion, industrial sites or terminal (MC_2) using a box-and whisker plot. ☆ represents clear MC_2 outliers deviating by -16.3 and 20.2 percent from the corresponding MC_1 means by more than three times the interquartile range (indicated by the whiskers) and ○ represents an outlier deviating by minus nine percent (more than 1.5 times the interquartile range). The box itself indicates fifty percent of the values around the median

The outliers, especially the two clear outliers, indicate that routine practices at the time of the study in some cases are insufficient to guarantee accurate measurement of the moisture content.

The mean moisture content (MC_1) was determined to be 39.3 percent for the winter deliveries 26.8 percent for the summer deliveriesand 35.1 percent of the weighted mean for all deliveries.

Standard deviations of variances in moisture content within and between deliveries (s_ε and s_β, respectively) obtained from the nested analysis of variance were 3.85 and 7.38, respectively. The F-value of s_β indicates that it is extremely significant ($p = 0.000$; null hypothesis H_0: $\sigma_\beta = 0$). The residuals were found to be somewhat positively skewed, resulting in different upper and lower 0.025 quantiles (2.209 and -2.009, respectively). The upper quantile and the within-delivery standard deviation of moisture content (s_ε) were therefore used to obtain conservative margins of error for the moisture content of a given delivery. Bootstrap estimates of the lower and upper 0.025 quantiles for the sample means, confirm that the constructed margins of error are conservative. For a three percent within-delivery margin of error at a ninety five percent confidence level, the required number of measurements was found to be nine. For accepted within-delivery margins of error of five, seven and nine percent the required numbers of measurements are three, two and one, respectively (fig. 3). In fact, with only one measurement the within-delivery margin of error was found to be ±8.5 percent.

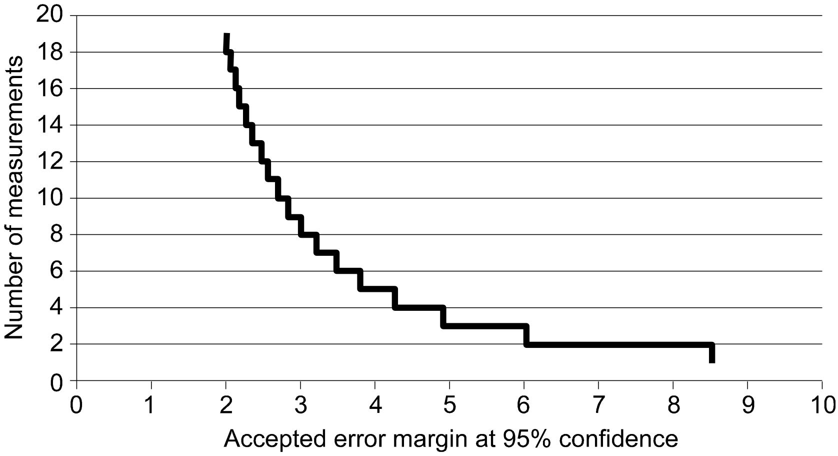

Fig. 3. The number of samples required to determine the moisture content within a delivery with accepted error margins between ±2 and ±8.5 percentage points

These results indicate that in most cases the current routine measurements of moisture content by the Timber Measurement Organization (MC_2 values) are sufficiently accurate. For a single delivery, however, a measurement may deviate from reference values by more than nine percent and hence substantially affect its estimated energy content and consequently its price.

Our results indicate that five samples are needed to meet the requirements outlined by the Swedish Forest Agency for estimating the dry weight of roundwood consignments. Since chipped logging residues usually come in sets of three containers it seems reasonable to recommend measuring at least six samples per delivery (two per container). In addition, although a delivery of chipped logging residue usually weighs less than fifty tons, it seems appropriate to use an accepted error of at most six percent, which usually applies to heavier deliveries. This is because a six percent error in moisture content reportedly corresponds to a 7.2 percent error in net calorific value per unit DM [Nylinder and Törnmarck 1986], and when multiplied by the dry mass, this can have an even larger impact on prices.

For the nested model (2) it is assumed that the variances within the deliveries σ_ε^2 are the same for all deliveries. That is, however, rejected by homogeneity tests of equal variances for both the moisture contents and the net calorific heating values. Therefore, a one-way analysis of variance was also performed for each season separately with delivery as a random factor for both moisture contents and the net calorific heating values. In table 1 estimates s_β and s_ε of σ_β and σ_ε respectively, are obtained for each season by one-way analysis of variance and for the total data by nested analysis of variance.

Table 1. The mean values and estimates of s_β and s_ε of σ_β and σ_ε obtained for each season separately by a one-way analysis of variance. Estimates are performed for both the moisture contents (MC) and the calorific heating values ($q_{v,net,d}$). The number of deliveries were twenty-nine in the winter and fifteen in the summer. The number of total measurements within deliveries were thirty except for one in the summer where twenty measurements were performed

Season	MC (%)			$q_{v,net,d}$ (MJ·kg^{-1} DM)		
	Mean	s_β	s_ε	Mean	s_β	s_ε
Winter	39.34	6.17	3.84	17.86	0.42	0.29
Summer	26.77	9.63	3.98	18.52	0.47	0.26
Total	35.73	7.50	3.89	18.08	0.44	0.28

The nested model (2) gives the variance of sample mean moisture content based on J deliveries and $K \geq 1$ moisture measurements within deliveries:

$$\sigma_\beta^2 / J + \sigma_\varepsilon^2 / (JK) \tag{3}$$

where σ_β^2 and σ_ε^2 are the variances between and within deliveries, respectively. Note that if there are no measurements of the moisture content the total variance is the same as if there is one measurement within a delivery ($K = 1$). The proportion of the total variance taken from the measurements within a delivery does not depend on the number of deliveries J:

$$\frac{\sigma_\varepsilon^2/(JK)}{\sigma_\beta^2/J+\sigma_\varepsilon^2/(JK)}=\frac{\sigma_\varepsilon^2/K}{\sigma_\beta^2+\sigma_\varepsilon^2/K} \tag{4}$$

If the total number of deliveries increases, however, the total variance decreases, which means that the influence of the number of measurements K will be of minor importance, as illustrated in figure 4.

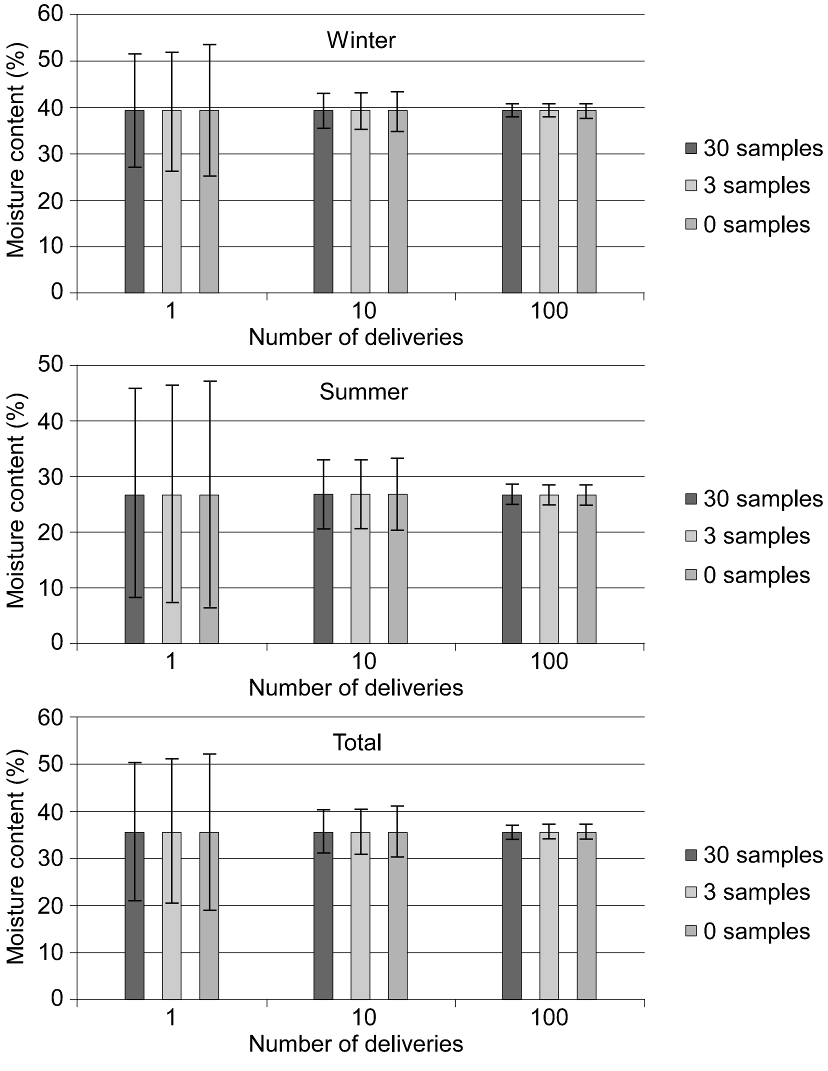

Fig. 4. The mean moisture content values, with 95 percent confidence intervals, obtained from thirty, three or zero samples per container of one, ten and 100 deliveries, for the 29 winter deliveries, fifteen summer deliveries and all 44 deliveries in total

A private forest owner who delivers a few deliveries per year is highly dependent on accurate measurement of his/her deliveries' moisture contents for correct payment. High precision is much less important for forest companies or large-scale forest owners who deliver numerous consignments annually, as the large number of deliveries will balance any discrepancies over time.

Conclusions

The results of this study show that current measurements of deliveries of comminuted logging residues by the Timber Measurement Association of Sweden are mostly sufficiently accurate, particularly for large-scale trade between forest companies and the energy industry. Inaccurate moisture content measurements, however, will significantly affect payments for private forest owners who only deliver logging residues once or a few times annually. To scale a single delivery accurately, it is essential to determine the moisture content using multiple samples. When delivering large amounts of chipped logging residues, on the other hand, the large number of deliveries serves to average out the variance in measured moisture content, and may even potentially make the measurement redundant.

Further studies are required to characterize differences between winter and summer deliveries in more detail, and timings of important changes. Further studies are also required to determine the effects of sampling positions in containers on the measurements, and the strength of the effects (if any) of taking moisture content measurements after unloading containers. The potential utility of other approaches for estimating deliveries' energy contents (for example volume measurements in conjunction with use of standard net calorific values per unit volume) also warrants attention.

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List of standards

EN 14918:2010. Solid biofuels – Determination of calorific value

EN 14778:2011. Solid biofuels – Sampling

EN ISO 18134-2:2015 Solid biofuels – Determination of moisture content – Oven dry method – Part 2: Total moisture – Simplified method

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