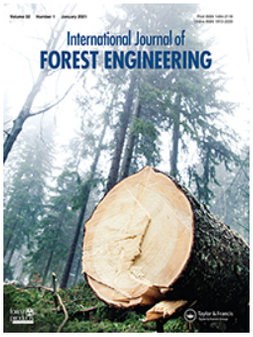

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Quality variation in comminuted forest fuels delivered during the winter in north Sweden

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ABSTRACT

Swedish legislation stipulates the precision required for estimates of parameters used to determine the value of various forest fuels. The net energy value of fuel, as it is received, is often used to set the trade price. The estimate of energy content is based on the moisture content of samples taken from each truckload and the weight of the biomass; the ash content and net calorific value are measured a few times each year. Hence, it is necessary to know the variation in moisture content to ensure that a sufficient number of samples are taken, a number based on the allowed variation and precision of estimates, as defined in the legalization. In this study, the variation in moisture content was measured by taking samples from 18 truckloads of comminuted forest fuels during the winter. The results showed that the current sampling regime, i.e., manually taking four samples from each truckload, is sufficient for deliveries with 10 truckloads for logging residue chips and 4 for stem wood chips. The number of samples should be increased to 12–43, 8–21, and, 17–82 depending on assortment for what the measuring act defines as large deliveries (>=50 tonnes; >=3 truckloads), medium-sized deliveries (<50 – >25 tonnes; 2 truckloads) and single truck deliveries (<= 25 tonnes; 1 truckload), respectively. Current research into fast online sampling and analysis methods could resolve this issue for small deliveries.

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Bioenergy; trade; chips; fuel quality; moisture content; representative sampling

Introduction

The use of primary (stem wood, branches, tops, needles, and stumps) and secondary forest biomass (chips, sawdust, and bark) for heat- and power generation is common in Sweden. In 2016, 47.6 terra watt-hours (TWh) of forest fuels were produced in Sweden, consisting of 43% primary forest fuels and 57% secondary products, mainly sawmill by-products (Swedish Energy Agency 2017). Primary forest fuels, direct from the forest, mostly consist of energy wood (logs not suitable for timber or pulp) and logging residues (branches and tops) from regeneration felling, but stumps and small diameter trees from thinnings can also be harvested if the market prices are high enough (Routa et al. 2013).

Forest fuel energy content is the most commonly used parameter for setting prices (Björklund 2014). The energy content is normally determined by using tabulated (pre-measured) values of the net calorific value and ash content and then calculating the net heating value based on fuel moisture content (MC) and mass at delivery. To improve the measurement precision of the effective heating values and ash content, samples are taken a few times each year for laboratory analysis, while MC samples are usually taken from all deliveries, e.g., from every truckload (Björklund 2014; Fridh 2017). The MC sampling is normally carried out manually by the truck driver or personnel at the point of delivery. The time it takes for the manual sampling work to be carried out depends on the measurement procedure and can take 5–15 minutes for each truckload. The sampling procedure must follow appropriate sampling processes as the comminuted biomass often forms different layers during transportation to the plant (Björklund 2014). This means material needs to be sampled from all layers, either in the truck, or on the ground after it has been unloaded.

The fuel properties measured for setting trade prices can be used for effective value chain management as it makes it possible to select the most suitable biomass for the current load on the boiler or to create mixes of different biomass types to achieve a uniform quality. There are also other fuel characteristics that are of relevance for the production process, e.g., fuel particle size distribution (PSD), which can affect the flow of the biomass to the boiler (Kons et al. 2015). The fuel particle size also affects how the fuel can be sampled and analyzed, as large particles require, for example, sampling tools with larger openings (EN ISO 18135:2017). Kons et al. (2015) showed that different particle sizes can have different MCs, with smaller particles generally having a higher MC.

In 2015, new legalization relating to the measurement of wood was introduced in Sweden which included forest fuels (SFS 1005 2014). Previous legalization only included sawtimber and pulpwood (SFS 209 1966) with measurement procedures and payment agreements being set through negotiation between the specific sellers and buyers. Currently, the legalization specifies a maximum allowed variation in the measurements that payments to forest owners are based on. The

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required precision differs depending on delivery size and whether the payment is based on energy content or weight (Skogsstyrelsen 2014). The new legalization requires the variation in the energy content to be: <20.0% for deliveries <25 tonnes dry weight; <15.5% for deliveries of 25–50 tonnes dry weight; <11.0% for deliveries >50 tonnes dry weight. In practice, this regulation means that the precision of measurements has to be 20.0%, 15.5%, and 11.0% for deliveries consisting of 1, 2, and 3 or more truckloads, respectively.

Thus, this means that it is important to understand the variation of MC and PSD in a fuel batch to enable the use of the correct sampling equipment, and to ensure enough samples are taken to achieve the legally-defined precision. Fuel property variation also depends on factors such as assortment, season, storage time, and comminution technique, making it necessary to investigate supplies under different conditions (Fernandez-Lacruz and Bergström 2017).

There have been studies of the MC of different kinds of wood chips (e.g., Gendek et al. 2018). However, most studies have investigated the mean MC in a truckload with a limited number of samples. Few studies have investigated in more detail the variation in MC (Björklund and Eriksson 2013; Hägg 2008; Nilsson et al. 2012). Most studies that have investigated this have been carried out in southern Sweden (Björklund and Eriksson 2013; Nilsson et al. 2012), while data from northern Sweden are limited (Hägg 2008). It is important to investigate whether there are any differences between different assortments, seasons, and comminution techniques as they could lead to a different number of samples being required to satisfy the legal requirements. Such differences would mean that appropriate sampling could be undertaken, rather than being based on a worst-case scenario, which would be costly.

The objective of this study was therefore to: 1) sample and analyze the MC, and PSD of comminuted wood fuels in northern Sweden at the point of delivery; 2) compare the precision and accuracy of measurements based on actual sampling procedures for payment and standards used for determining the true values (reference measurements); 3) compare the variation in MC and PSD of different assortments; 4) estimate the number of samples needed for each truckload or delivery to achieve a specified measurement precision.

Materials and methods

The sampling in the study was carried out on every weekday between January 21 and February 14, 2013, at Hedensbyn, a combined heat- and power plant run by Skellefteå Kraft AB in Skellefteå, Västerbotten county, Sweden (64°44′40”N 21° 02′33”E). During those 3 weeks, the average temperature in the area around Skellefteå was −7.8°C (ranging from −0.1 to −15.3°C) (SMHI 2016a), there was sleet and snow from January 26th to February 14th, and the mean daily precipitation was 1.5 mm (ranging from 0.1 to 4.6 mm) (SMHI 2016b). During this period, 18 truckloads of comminuted forest fuel assortments were randomly sampled from all the trucks making deliveries. Also, data about how the material in each truckload had been treated were collected from the suppliers (Table 1).

For each truckload, the fuel chips were sampled using the normal sampling protocol at Hedesbyn used during 2013. This process involved the truck driver tipping the material onto the ground in a pile and taking four samples (each about 2.5 l) at approximately 1 m height from arbitrary selected different parts of the pile. These four samples were then mixed into a general sample. Chips were sampled using a scoop with an opening of 178 mm. This size of scoop was chosen on the assumption that 95% of fuel dry weight would consist of particles with all dimensions smaller (d_{95}) than 70 mm. One sample of 0.5–1 l was taken from the general sample for MC analysis.

The fuel chips analyzed in the study were then sampled following the standards: EN ISO 18135:2017 for solid biofuels sampling; SS-EN 14780:2011 for sample preparation; an simplified method of SS-EN 14774–2:2009 for the determination

Table 1. Information on the 18 truckloads of forest fuel used for analysis. L = logging residue chips from clear-cuts; S = stem wood chips from low-quality round wood; Mix = mix of L and S. – indicates missing data.

				Storage time (days)			
Truck no.	Assortment	Comminution method	Raw weight (tonnes)	In-stand before extraction	At landing	When comminuted	Covered during storage at landing*
1	L	Chipped	28.02	223	31	0	Yes
2	L	Chipped	36.66	162	92	0	Yes
3	L	Chipped	39.73	163	92	0	Yes
4	L	Chipped	34.22	-	-	0–2	Yes
5	Mix	Crushed	36.21	-	-	0–2	No
6	Mix	Crushed	38.00	-	-	0–2	No
7	L	Chipped	28.26	322	-	0	Yes
8	L	Chipped	19.50	323	-	0	Yes
9	L	Chipped	36.85	294	90	0	Yes
10	L	Chipped	25.14	298	90	0	Yes
11	L	Chipped	35.44	268	152	0	Yes
12	L	Chipped	36.96	269	152	0	Yes
13	L	Chipped	35.31	178	61	0	Yes
14	S	Chipped	34.78	88	-	0–2	No
15	L	Chipped	34.60	244	31	0	Yes
16	S	Chipped	34.14	93	-	0–2	No
17	L	Chipped	25.60	-	-	0	Yes
18	L	Crushed	39.35	-	-	60–90	No

*Cover with a strong paper-based laminate (cf. Eliasson et al. 2020) during storage at the roadside

of MC using the oven dry method; and part 1 of SIS-CEN/TS 15149–1:2006 for the determination of PSD.

The unloaded fuel chips were sampled by taking 5 L samples from 30 different sampling points systematically located throughout the pile (or piles) (Figure 1). The surface layer (~2 cm) was removed from the pile before the sample was taken. The piles were divided into three vertical layers of equal height and the number of samples taken from each layer was proportional to its estimated (relative) volume. The top, middle, and bottom layers were assumed to comprise 20%, 30%, and 50% of the total volume, respectively. The samples were taken from the middle of each layer with the same scoop used for the normal sampling process. Afterward, the samples were kept cool (<0°C) in plastic buckets with airtight lids until the sample preparation was carried out (within 0–36 h).

Twenty of the 30 samples from each truckload were split to estimate the in-sample variation. The sample preparation was carried out on a stainless steel bench using plastic scrapers, following the quartering method. Sub-samples, with and estimated weights of between 300 and 500 g, were put in paper bags (of known weight) and were then scaled of mass. The bag and material were then dried for 48 h at 105°C. The bench and scraper were cleaned between the preparations of samples from different sample points. Samples were weighed with a set of scales to an accuracy of 0.1 g.

After MC determination, the dry samples were then sieved to determine the PSD. The sieving was done in late June and in July 2013 to allow for the material to reach fiber saturation point again before sieving. All the dried material from one sampling point was sieved together (i.e., split samples were combined). The sieving was carried out with circular sieves of diameter 200 mm. The relative quantity of material in each particle size category and d_{95} were then calculated for each truckload and assortment.

Statistics

Calculations of the variance and precision of the MC measurements (preparation and testing variance (V_{PT}), primary increment variance (V_I), and the overall precision (P_L)) were made following the EN ISO 18135:2017 standard. The relative precision (P_R) was then calculated based on the P_L and the mean MC in the truckload. These values were used to estimate the required number of samples (n_{min}) needed from each truckload to reach the P_R as determined by the delivery size, defined by Swedish legalization. The estimates of n_{min} were made for the means of V_{PT}, V_I, and MC, and the mean plus the 95% confidence interval for V_{PT} and V_I, and the mean minus the 95% confidence interval for MC. The 95% confidence interval was assumed to meet the legal requirements, while the mean measurements may prove useful for other situations. The results were also compared to the measurement practice at Hedensbyn (used in 2013) to evaluate any variations from the true value.

Analysis of variance (ANOVA) and analysis of covariance (ANCOVA) tests were carried out to investigate any significant effects influencing n_{min} (Table 2). ANOVA and ANCOVA also investigated differences between different layers in the piles (Table 2).

Correlation analysis gave estimates for the correlation coefficient (r) and p-value (pv), and was used to investigate any correlations between the continuous and independent variables. In-stand storage time and storage time at the landing were tested against MC and P_L; MC was tested against P_L, relative standard deviation, V_{PT} and V_I; MC was tested against all particle size classes and d_{95}. Variables with no correlation to a continuous variable were then tested using ANOVA against the factors, while the variables with a correlation were tested using ANCOVA (Table 2). Tukey's Honest Significant Difference test (Tukey's test) of means was used to test the intra-significance of factors with more than two levels. The Shapiro-Wilk's Normality Test was used to test for normality of residuals in the ANOVA and ANCOVA tests, when possible the response variable was transformed to achieve normality. The Kruskal Wallis rank sum test was used if the residuals were not normally distributed. The pairwise Wilcoxon rank sum tests were used to test intra-significance of factors with more than two levels.

A paired t-test was carried out to investigate whether there were any differences between the reference mean MC in our

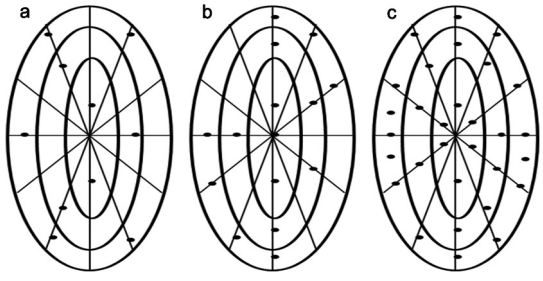

Figure 1. Schematic sketch of piles seen from above. Each pile was divided into 12 sections, each section approx. 30°, and with three layers of equal height. Sketch A shows sampling when three piles were created from each truckload (10 sampling points per pile), B shows sampling for two piles (15 sampling points per pile) and C for one pile (30 points).

Table 2. Factors and response variables in the ANOVA and ANCOVA for mean values in measured truckloads. MC = moisture content, wet basis, VPT = variation within samples, VI = variation between samples, PL = absolute precision, PR = relative precision, d_{95} = 95% of the chips dry weight have all dimensions below 70 mm, and the relative percentage of particles between 0–3.15 mm, >3.15–8 mm, >8 – 16 mm, >16 – 31.5 mm, >31.5–45 mm, >45 – 63 mm, >63 – 100 mm, and >100 mm. The general equation $y_{ij} = \mu + \alpha_i + \beta_j + \delta(X_{ijl}-\bar{X}\bullet\bullet\bullet) + e_{ij}$ was used, where y_{ij} was the response variable, μ was the true value, α_i, β_j were factors, $\delta(X_{ijl}-\bar{X}\bullet\bullet\bullet)$ was a covariate, and e_{ij} was the random deviation.

	Factor		
y_{ijk}	α_i	β_j	$\delta(X_{ijkl}-\bar{X}\bullet\bullet\bullet)$
MC	assortment	comminution method	-
V_I	assortment	comminution method	MC
V_{PT}	assortment	comminution method	-
P_L	assortment	comminution method	-
P_R	assortment	comminution method	-
d_{95}	assortment	comminution method	-
0–3.15	assortment	comminution method	MC
>3.15–8	assortment	comminution method	-
>8–16	assortment	comminution method	MC
>16–31.5	assortment	comminution method	-
>31.5–45	assortment	comminution method	-
>45–63	assortment	comminution method	-
>63–100	assortment	comminution method	MC
>100	assortment	comminution method	-
Particle size	layer in pile	-	-
MC	layer in pile	-	-

study and the samples collected by the drivers. The samples taken by the drivers were also compared at the truckload level to the values measured in our study using a one-sample t-test. These tests resulted in a correction to the pv for multiple testing, which was carried out using Holm's method (Snowdon 1991). The Shapiro-Wilk's Normality Test was used test for normality and if the variable could not be transformed to reach normality, the one sample Wilcoxon test was used. All statistical tests were carried out using RStudio Version 1.1.463 (RStudio Team 2015) with a significance level of 5%.

Results

There was a significant correlation between in-stand storage time and MC, and between V_I and MC, while the other interactions had no significance correlation (Table 3). Therefore, MC was used as a covariate in the ANCOVA to evaluate the effects of the factors assortment and comminution on V_I.

The assortment factor significantly affected the MC and P_L, while the comminution method factor was not significant (Table 4). There was no significant effect of the factors on V_I, V_{PT}, and P_R according to ANOVA and ANCOVA. Tukey's test showed a significant difference in MC between stem wood chips and logging residue chips (pv = 0.004), but not between logging residue chips and mixed chips (pv = 0.648) and stem wood chips and mixed chips (pv = 0.085). Tukey's test also showed that there were significant differences in P_L between logging residuechips and stem wood chips (pv = 0.027) and between logging residue chips and mixed chips (pv = 0.045), but not between stem wood chips and mixed chips (pv = 0.841).

There were significant correlations between the average MC for each truckload and the relative weight for particle sizes 0–3.15 mm, >8 – 16 mm, and >63 – 100 mm, while the other interactions had no significant correlation. Therefore, MC were used as covariate in ANCOVA to evaluate the effects of the factors assortment and comminution method on particle size.

The assortment factor significantly affected the relative quantity of material in size classes >3.15–8 mm and >16 – 31.5 mm while comminution method had no significant effect according to the ANOVA (Table 4). The factor assortment significantly affected the relative quantity of material in the size classes 0–3.15 mm, while comminution method and the covariate MC had no effect according to the ANCOVA. There was no significant effect of the factors on the relative weight of particles sized >8 – 16, >31.5–45, >45 – 63, and >63 – 100 mm or for the d_{95} value according to ANOVA and ANCOVA. Tukey's test showed that there were significant differences between the relative quantity of particles measuring 0–3.15 mm for logging residue chips and stem wood chips

Table 3. Correlation analysis between moisture content (MC) and in-stand storage time (in stand), storage time at landing (in land), absolute precision (PL), relative precision (PR), variation within samples (VPT), and variation between samples (VI). Correlation analysis between PL and in stand and in land. Correlation analysis between MC and the relative percentage of particles between 0–3.15 mm, >3.15–8 mm, >8 – 16 mm, >16 – 31.5 mm, >31.5–45 mm, >45 – 63 mm, >63 – 100 mm, >100 mm, and 95% of the chips dry weight have all dimensions below (d_{95}).

	Correlation between MC and PL and other variables									
	in stand	in land	PL	PR	VPT	VI				
MC	r-0.803 pv = 0.001	r = −0.362 pv = 0.182	r = 0.433 pv = 0.073	r = −0.141 pv = 0.208	r = −0.141 pv = 0.208	r = 0.537 pv = 0.022				
PL	r = −0.011 pv = 0.972	r = −0.266 pv = 0.337								
	Correlation between MC and relative particle size and d_{95}									
	0–3.15	>3.15–8	>8 – 16	>16 – 31.5	>31.5–45	>45 – 63	>63 – 100	>100	d_{95}	
MC	r = 0.542 pv = 0.020	r = 0.277 pv = 0.365	r = −0.486 pv = 0.041	r = −0.421 pv = 0.082	r = −0.167 pv = 0.511	r = 0.365 pv = 0.137	r = −0.493 pv = 0.038	r = 0.240 pv = 0.319	r = 0.223 pv = 0.373	

Table 4. Mean values and standard deviation (sd) observed for trucks transporting different forest fuel assortments. The p-values from the ANOVA and ANCOVA for the continuous variable are shown with the assortment factor (Asort), comminution method (commu), and the covariate (cov) MC, and for Shapiro-Wilks normality test (S-W). MC = moisture content, wet basis, V_{PT} = variation within samples, V_I = variation between samples, P_L = absolute precision, P_R = relative precision (%), d_{95} = 95% of the chips dry weight have all dimensions below 70 mm, and the relative percentage of particles between 0–3.15 mm, >3.15–8 mm, >8 – 16 mm, >16 – 31.5 mm, >31.5–45 mm, >45 – 63 mm, >63 – 100 mm, and >100 mm. Mean values with different superscript capital letters in rows differ significantly. NA = data missing. Bold values indicate significant p-values.

	Logging residues chips		Stem wood chips		Mixed chips		ANOVA/ANCOVA			
Parameters	Mean	sd	Mean	sd	Mean	sd	Asort	commu	cov	S-W
MC	49.77^{BA}	7.09	28.96^{C}	1.20	45.05^{CA}	4.28	**0.004**	0.907	-	0.999
V_{PT}	5.19^{A}	2.66	1.74^{A}	1.56	1.88^{A}	0.11	0.089	0.275	-	0.270
V_I	47.40^{A}	29.32	7.30^{A}	9.75	6.42^{A}	3.23	0.064	0.766	0.180	0.086
P_L	5.04^{A}	1.34	2.63^{B}	1.43	2.89^{B}	0.15	**0.026**	0.355	-	0.968
P_R	10.30^{A}	2.97	9.19^{A}	5.32	6.47^{A}	0.95	0.297	0.510	-	0.374
d_{95}	77.43^{A}	39.70	35.00^{A}	7.07	74.50^{A}	65.76	0.371	0.119	-	0.286
0–3.15	23.00^{A}	4.93	8.10^{B}	3.52	20.59^{A}	4.67	**0.009**	0.228	0.924	0.085
>3.15–8	25.75^{A}	3.23	21.43^{A}	8.60	35.92^{B}	5.30	**0.008**	0.888	-	0.273
>8 – 16	28.48^{A}	3.34	35.97^{A}	6.61	27.30^{A}	1.75	0.054	0.958	0.593	0.903
>16 – 31.5	15.76^{A}	4.23	29.49^{B}	16.58	9.73^{A}	4.22	**0.014**	0.714	-	0.181
>31.5–45	1.20^{A}	0.65	1.63^{A}	1.08	0.50^{A}	0.24	0.262	0.413	-	0.067
>45 – 63	0.22^{A}	0.11	0.33^{A}	0.24	0.00^{A}	NA	0.207	0.502	-	0.286
>63 – 100	0.04^{A}	0.04	0.16^{A}	NA	0.11^{A}	NA	0.312	0.523	0.487	0.285
>100	5.66^{A}	2.46	2.98^{A}	0.72	5.90^{A}	3.68	0.080	<0.001	-	0.763

(pv = 0.005), pv =, but not between stem wood chips and mixed chips (pv = 0.082) or logging residue chips and mixed chips (pv = 0.783). Tukey's test also showed that there were significant differences between the relative number of particles measuring >3.15–8 mm for stem wood chips and mixed chips (pv = 0.009) and between mixed chips and logging residue chips (pv = 0.014), but not between stem wood chips and logging residue chips (pv = 0.373). Tukey's test showed that there were significant differences between the relative quantity of material sized >16 – 31.5 mm for stem wood chips and logging residue chips (pv = 0.025) and between stem wood chips and mixed chips (pv = 0.015) but not between logging residue chips and mixed chips (pv = 0.414). The comminution method factor affected the relative quantity of material in the size class >100 mm while assortment had no significant effect according to ANOVA (Table 4). On average, 4.80% (sd 1.32) of material that had been chipped was in the size class >100 mm while, for the same size class, the average was 8.35% (sd 4.99) for crushed material.

There were no significant differences between the MC values for the different layers in the piles (pv = 0.052). Shapiro-Walk's normality test showed normally distributed residuals (pv = 0.976). On average, the top layers had a MC of 47.77% (sd 9.35), the middle layers 47.39% (sd 9.34), and the bottom layers 46.29% (sd 9.12). There were significant differences for the relative quantity of material of different particle sizes in relation to several different factors for the layers (Table 5).

The paired t-test between the averages of samples, taken by the truck drivers, and reference samples showed a significant difference (pv = 0.014) with the majority of the samples taken by the drivers having a lower MC (Figure 2). The Shapiro-Walk's normality test showed normally distributed residuals (pv = 0.701). Eleven of the samples that had been taken by the drivers significantly differed from the mean values of the reference samples, when the samples collected by the drivers were compared at truckload level to the reference samples, based on a one-sided t-test (Figure 2). Three of these eleven samples predicted higher MCs than given by the reference sampling.

Sampling of each delivery

For the three assortments, different estimations for the number of samples needed to meet legal requirements were made, given that ANOVA and ANCOVA detected differences between the assortments. All assortments could be measured using the measurement process used in 2013 at Hedesbyn when the mean values of V_I, V_{PT}, and MC were used to estimate the number of samples needed to meet legal requirements (Figure 3). However, logging residue chips and stem wood chips could not be measured adequately using the 2013 measurement process when the mean of V_I, V_{PT} plus a 95% confidence interval, and the MC minus a 95% confidence interval was used. Deliveries of logging residue chips had to consist of 10 truckloads in order to ensure that four samples were sufficient to measure with the legally-defined precision. Deliveries of 1, 2, and 3 truckloads required 43, 21, and 82 samples, respectively, to measure with the legally-defined precision. Deliveries of stem wood chips had to consist of six truckloads before four samples were enough to measure with the legally-defined precision. Deliveries of 1, 2, and 3 truckloads required 12, 8, and 17 samples, respectively, to measure with the legally-defined precision.

Discussion

On average, the MC in our study was about 10% higher than Nilsson et al. (2012) reported for winter conditions in southern Sweden, while the sd was similar. The MC that Björklund and Eriksson (2013) reported was closer to the MC in our study, but the sd was smaller. This highlights the importance of investigating these factors in different locations. The choice of variance (mean or with 95% confidence interval) clearly had a large impact on the number of samples required to achieve a particular relative precision when estimating the MC. It is, therefore, important to consider which variance should be used as it affects the number of samples that need to be taken from each delivery, and also possible delivery sizes. Using the mean variance is easier from a practical perspective as fewer samples are required. However, about 50% of the deliveries would then not fulfil the legal requirements, which would probably be unacceptable. Means with a 95% confidence interval should be used for the MC measurements if the energy content is to be the basis of payment to forest owners, while the use of means may prove interesting in other situations not legally regulated, e.g., from feed-in terminals to industry (Väätäinen et al. 2017).

Table 5. Relative quantity of material of different sizes in the top (T), middle (M), and bottom (B) layers given as mean ($\bar{y}$) and standard deviation (sd) values. Different superscript capital letters in columns indicate significant differences.

	Particle size class (mm)															
	0–3.15		>3.15–8		>8–16		>16–31.5		>31.5–45		>45–63		>63–100		>100	
Layers	$\bar{y}$	Sd	$\bar{y}$	sd	$\bar{y}$	sd	$\bar{y}$	sd	$\bar{y}$	sd	$\bar{y}$	sd	$\bar{y}$	sd	$\bar{y}$	sd
B	20.05^{B}	6.64	25.90^{A}	5.27	30.04^{A}	4.73	17.12^{A}	7.00	0.92^{A}	0.64	0.22^{A}	0.30	0.01^{A}	0.04	5.74^{A}	2.62
M	23.36^{A}	7.96	27.11^{AB}	5.28	28.09^{B}	4.70	15.27^{AB}	7.02	1.30^{A}	1.06	0.11^{AB}	0.24	0.04^{A}	0.16	4.72^{AB}	2.36
T	25.71^{A}	8.81	28.38^{B}	5.52	26.37^{C}	4.55	13.93^{B}	7.68	1.28^{A}	0.94	0.03^{B}	0.11	0.04^{A}	0.15	4.26^{B}	3.19
	P-values form ANOVA, Shapiro-Wilk's normality test (S_W), and Kruskal Wallis rank sum test (KW)															
ANOVA	<0.001		<0.001		<0.001		<0.001		0.396						0.027	
S-W	0.261		0.358		0.301		0.492		0.433		0.033		<0.001		0.438	
KW											<0.001		0.410			
	Tukey's pairwise tests and Pairwise Wilcoxon rank sum tests, P-values															
B-M	0.008		0.082		0.010		0.055		0.344		0.076		0.700		0.152	
B-T	<0.001		0.002		<0.001		0.001		0.387		0.001		0.490		0.024	
M-T	0.073		0.063		0.026		0.205		0.996		0.070		0.490		0.700	

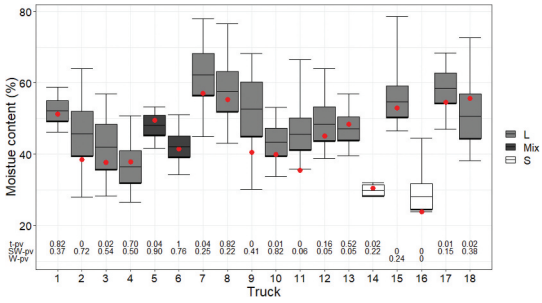

Figure 2. The moisture content for different truckloads, 95% confidence intervals around the mean, minimum and maximum observation based on the reference sampling. The value of the sample taken by the driver is marked with a red dot. L = logging residue chips, S = stem wood chips, Mix = mixed chips. The p-value from the one-sided t-test (t-pv) between the drivers' sample and the mean value of the reference sample, Shapiro-Wilk's normality test (SW-pv), and one sample Wilcoxon test (W-pv) is shown just above the x-axis. A p-value of 0 indicates it was <0.01.

Using the 95% confidence interval means that a larger number of samples would have to be taken at Hedesbyn in 2013, at least for smaller deliveries of logging residue chips and stem wood chips (Figure 3). More than 10 truckloads in each delivery are needed to meet the legal requirements with the measuring process used in 2013 at Hedesbyn for logging residue chips, while stem wood chips need four truckloads in each delivery. Only the mixed chip loads in this study met the legal requirements with a reasonable number of samples. It is also important to note that it was assumed that only the measurement of MC contributed to the variation around the true value. In reality, there will also be errors from other sources, e.g., truck weighing scales. It is possible to use different measurement processes for materials with different V_I, V_{PT}, and MC. The results in our study indicate that MC and P_L differ between assortment, but not as a result of different comminution methods. However, the use of different measurement processes increases the risk of human error. In addition, there could be uncertainty about the number of truckloads that constitutes one delivery and too few samples might accidently be taken. It is, therefore, probably best to design the measurement procedure based on the requirements for small deliveries where the goal is to have the payment based on the fuel quality at individual landings. This exceeds the number of samples stated by Björklund and Eriksson (2013) that are needed to meet the legal requirements, mainly due to the lower variation in their data. This further points to the importance of investigating this in several locations and different seasons.

In practice, it might be possible to double or triple the number of samples taken by the driver, meaning eight or twelve samples from each truckload. In that case, 12 samples would meet the requirements for logging residue chip deliveries with five or more truckloads, and for stem wood chips deliveries with four or more truckloads. It is not realistic to increase the sample size further, as long as the sampling is done manually by the driver due to the strain of sample collection. However increased sampling would lead to increased cost for the receiver. For small deliveries, more than 12 samples are needed, which indicates that the sampling procedure needs to be automated. There are ongoing attempts to develop new-automated technology for sampling and measuring that should be faster and more precise, but these are currently not used. However, use in the future is likely (Samuelsson et al. 2006; Fernandez-Lacruz and Bergström 2016; Fridh 2017). Better and faster measurements can also be beneficial for the production process as fuel can be combusted before the results from the oven drying method are available. The downside is that these fast and accurate measurement techniques would require a large investment, and would probably only be feasible for large receivers, making it uneconomic for small receivers to use forest biofuel.

Another option is to change the definition of a delivery, such that material from more than one landing is included in one delivery. For example, pulpwood is measured from collectives where certain parameters are estimated for all included landings, e.g., the percentage of wood unsuitable for pulp is measured as an average for all landings in a collective (Biometria 2020). It could be possible to establish similar measurement collectives for comminuted forest fuel. There is some flexibility in standard EN ISO 18135:2017 as to what a delivery can consist of. A delivery is a quantity of fuel with similar characteristics that is delivered over a specific period. The delivery cannot exceed 2500 tonnes, if it is sampled manually, while there is no restriction for mechanically sampled deliveries. The period that constitutes a delivery could thus be all truckloads received over a day, week, month, or season. How the parties define a delivery will greatly influence the number of samples required to meet legal requirements.

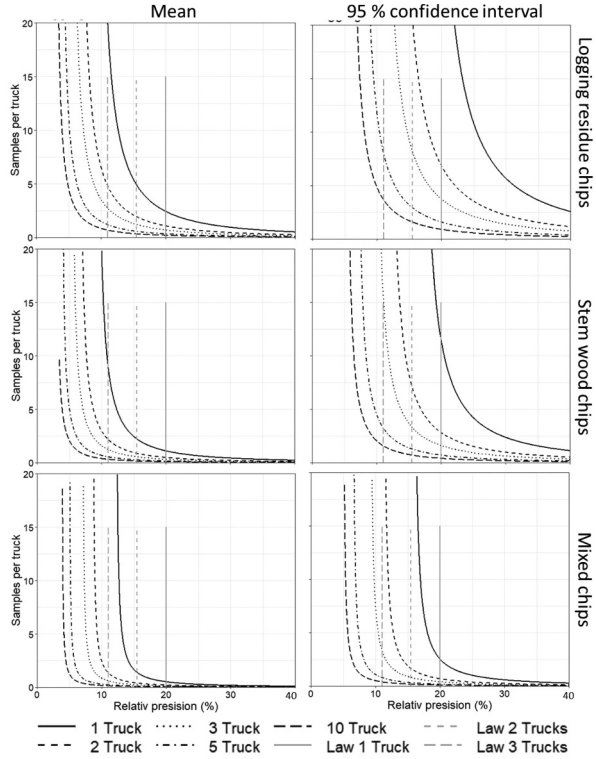

Figure 3. Estimated number of samples needed for each truckload to achieve different relative precisions, depending on the number of truckloads in a delivery. Calculations were based on mean values for the variance and MC, the mean of VI, VPT plus a 95% confidence interval, and the MC minus a 95% confidence interval for logging residue chips, stem wood chips and mixed chip deliveries.

Deliveries over longer periods with truckloads from several landings would help to overcome many of the problems associated with meeting the new legislation.

The actual precision that is required varies with MC, as the legalization defines a relative precision. This requirement means that V_I, V_{PT}, and MC are important for the correct estimation of P_R. Therefore, an expected MC must also be predicted when estimating the number of samples needed for a set P_R. It is probably most appropriate to use historical data from measurements to estimate the expected MC for different seasons. This means that the results in our study are only valid for winter conditions in northern Sweden and in similar weather conditions as during the time span of the study. Different V_I, V_{PT}, and MC should be established for different seasons and regions.

The handling of the material before delivery only had a small influence on the MC, V_I, V_{PT}, and PSD. The only significant difference was seen in materials that were stored longer in-stand before forwarding to the landing, where they had a lower MC. This result is in line with previous studies into the storage of logging residues that showed an extended storage time, over at least one summer, reduced the MC of logging residue chips (Nurmi 1999). Our study also showed that chipped materials, compared to those that had been crushed, contained fewer sticks over 100 mm. Oversize particles are to be avoided since they may cause problems in fuel feeding systems, e.g., conveyor belts, feeding screws, etc., and thus increase the risk of obstructing the fuel supply to the boiler (Rackl and Günthner 2016). Our results also showed indications that a larger proportion of small particles lead to a higher MC. Material with more small particles was also found to have a higher MC, as reported in, for example, Kons et al. (2015). These results indicate that the fuel quality could be improved if logging residues were stored longer before comminution, if as much material as possible were chipped instead of crushed, and if fine particles were sieved off before delivery (Kons 2019). These adjustments should reduce the MC of the fuel and the relative quantity of material with all dimensions greater than 100 mm.

There was a difference between the samples taken by the drivers and the mean estimated for each truck in our study (Figure 2). This was as expected, as the results in our study showed that four samples would not be enough to meet the legal requirements for a single truckload of logging residue chips and stem wood chips; previous studies have noted differences between these measurements (Björklund and Eriksson 2013). However, many of the samples taken by the drivers had a significantly lower MC than the reference mean measured in our study, while a few had a higher MC (Figure 2). This indicates that the drivers could be taking somewhat dryer samples than the reference mean, but we do not believe it is, in any way, intentional. The main reason for this error is probably that larger blocks of fine particles were often frozen together, and these are very time-consuming to sample, meaning the drivers do not collect samples from these blocks. The error could also be affected by the movement of particles when the material is tipped from the truck. The results showed that the bottom layer had a greater number of large particles than the top layer, while the top layer had more fine particles (Table 5). Fines are often moister and large particles are often dryer (Kons et al. 2015), even though no difference in MC was found between the layers in the piles in our study. The majority of samples are taken from the bottom part of the pile, if the sampling instructions are followed correctly, which should lead to a sample with a greater number of larger particles. The second error can be corrected by changing the sampling procedures, while the first probably cannot be corrected as it would be too time-consuming for the drivers to sample frozen material.

The results of our study could be slightly affected by the size of the scoop used for sampling. There was no difference for d_{95} between assortments, even though logging residue chips and mixed chips had a larger proportion of material in the small size classes. However, when the variation in d_{95} is considered, it seems that the scoop currently used is not guaranteed to have an opening at least 2.5 times larger than the d_{95} in 95% of deliveries. The scoop should have an opening of 300–310 mm. This could lead to an underrepresentation of large particles, which would produce a slight underestimate of the MC (cf. Kons et al. 2015). Also, re-moistening of the samples after they have been removed from the oven before weighing could impact the results. The usual increase in weight between the first and last samples was 0.1–0.2 g, corresponding to 0.04–0.11% of the dry weight of the samples. This increase is not unreasonable for samples measured no more than roughly 1 min from when they are taken out of the oven (Gustafsson 2016). However, we believe that these two error sources only had a small impact on the results. It is also important to note that there were only two truckloads of stem wood chips and two of mixed chips, meaning that the results for those assortments should be treated with caution.

Conclusions

The measurement practice used in 2013 at Hedesbyn cannot process deliveries that consist of a few truckloads with the required legal precision. Therefore, either more samples from each truckload are needed or more truckloads for each delivery are needed. More samples can be taken manually up to a point, but mechanical sampling is still needed for the smallest deliveries as they require over 40 samples. An alternative is to include more truckloads in a delivery. Trucks delivering the same assortment from a set geographical area could be combined to give a collective measurement. In the near future, such collective measurements are likely to be the only realistic solution. However, there are many ongoing projects developing fast on-line measurements that should make accurate mechanical measurement possible in the future (cf. Fridh 2017). It is also important to highlight that it is not just the measurement of MC that determines the overall precision of measurements of energy content.

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