Windrowing and fuel-chip quality of residual forest biomasses in northern Sweden

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Abstract

Utilization of forest residual biomasses, including logging residues (LR) and whole tree-parts (WT), in Fennoscandia is expected to increase in response to increases in demand from the bioeconomy. LR and WT are often seasoned in windrows at roadsides, and more knowledge (prior to comminution) of their dry mass content would be highly useful for logistic planning and value estimations. Therefore, we described and compared windrow fuel-chip quality and storage conditions of LR and WT delivered in one season to the same energy plant by the same supplier. Seventy-six windrows in northern Sweden were surveyed and chipped. Twenty-five were also sampled to assess their moisture content (MC), ash content (AC) and particle size distribution. The mean MC (45%) did not significantly differ between LR and WT, but varied substantially within and between sites. LR fuel-chips had higher AC than WT (2.4% vs. 1.5%) and two-fold higher proportions of fines and oversized fractions (12.2 vs. 5.8% and 2.2 vs. 1.1%, respectively). LR windrows fully exposed to ambient conditions had 6.7% lower MC (43%) than sheltered counterparts. Average bulk densities of LR and WT were 66 and 59 dry kg per bulk cubic metre, respectively. The results enable development of models for estimating LR or WT windrows' dry mass contents, show effects of some storage conditions on MC, and highlight needs for holistic supply chain management for cost-effective delivery of high-quality residual forest biomasses.

Keywords: bioenergy; biomaterial; small-diameter trees; logging residues; conversion factor; storage.

Introduction

In 2015, fuel-chips from Swedish primary forest fuels amounted to 3.3 M dry tonnes (t), with logging residues (LR; tops and branches), energy wood (discarded low-quality industrial roundwood), small-diameter undelimbed trees and stumps accounting for 59%, 32%, 8% and 1%, respectively (SCB 2016). However, large amounts of potential forest residual biomasses in Fennoscandia are not currently utilized (Routa *et al.* 2013). For example, at least 4.3 M dry t of small-diameter trees from early thinning forests (Fernandez-Lacruz *et al.* 2015) and ~1–2 M dry t from sites such as overgrown farmland, roadsides and power line corridors (Andersson *et al.* 2016) could be sustainably harvested in Sweden annually. Demand for forest biomass is expected to increase in the bioeconomy (Mantau *et al.* 2010; Hetemäki *et al.* 2014), as by-products from traditional forest industries are already extensively utilized (SDC 2015).

In Sweden, payments for comminuted biomass are usually based on amounts of delivered energy, determined at the energy plant (hereafter, plant) by scaling truckloads and moisture content (MC) sampling. Like pulpwood, payments for energy wood are mostly estimated by measuring stack (frame) volumes. Payments for uncomminuted assortments (such as bulk LR or whole tree-parts, WT) depend on weight measurements, which rarely include MC sampling (Björklund 2014). Forest fuels are mainly comminuted at forest roadsides/landings, but sometimes at terminals or end-users' facilities. Bulk LR and WT are stored in windrows at roadsides for drying and balancing supply and demand. Demand is highest in winter, although forest fuels are produced year-round. Windrowing leads to lower dry matter losses than storing fuel-chips (Jirjis 1995), although handling costs are higher (Nurmi & Hillebrand 2007). The season the forest fuel is harvested, forwarded and chipped, together with harvest and storage methods, influences fuel-chip quality; placing and covering windrows properly enhances drying (Jirjis *et al.* 1989; Jirjis & Lehtikangas 1993; Lehtikangas & Jirjis 1993, 1995; Lehtikangas 1999; Nurmi 1999; Björheden 2010; Filbakk *et al.* 2011a, 2011b; Björheden *et al.* 2013). Meteorological variables have been considered when developing models for forecasting MC of windrows and their optimal seasoning time (Routa *et al.* 2015). Ash content (AC), usually determined several times per year at the plant, can decrease during seasoning through shedding of nutrient-rich fractions (Pettersson & Nordfjell 2007). An assortment's gross calorific value depends on its natural ash and chemical composition, but its net calorific value largely depends on its MC and contaminating ash (Thörnqvist 1984). Incorrect handling can lead to pollution with mineral soil, stones, etc., resulting in increases in AC and possible ash-handling problems in the furnace (Khan *et al.* 2009). High coarse and fine fraction contents may impair feeding and combustion in the boiler (Bäfver & Renström 2013). The particle size distribution (PSD) can be influenced by chipper configuration, knife sharpness, temperature and MC (Lehtikangas 1999; Eriksson *et al.* 2013). Extensive studies of LR and WT fuel-chips have shown that their MC after storage is affected (*inter alia*) by handling, storage length and weather, but harvest season and raw materials also affect initial MC. However, AC values are generally slightly higher for LR than WT, due its lower stemwood fractions and higher bark and needle contents; reported values are 2.5 vs. 2.0% (Ringman 1996), 1.6–2.2 vs. 1.0–1.2% Pettersson & Nordfjell (2007), 2.3 vs. 0.9% (Nordhagen 2014) and 2.9 vs. 1.7% (Kons *et al.*

2015). Kons *et al.* (2015) also found higher contents of fines and coarse fractions (hereafter, particles <3.15 mm and >63 mm, respectively) in LR chips than in WT chips.

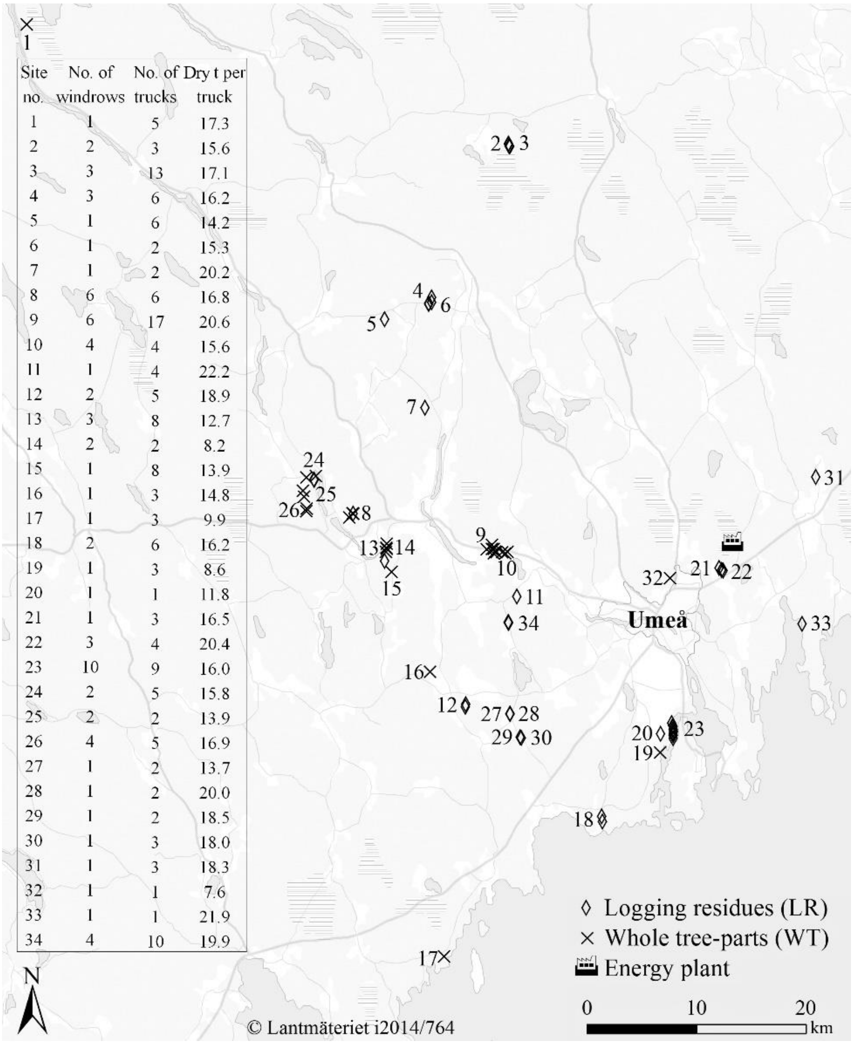
Transport of bulk LR and WT is often limited by volume rather than mass, resulting in sub-optimal machine payload utilization. Mattsson (1992) reported solid volume contents of 15–20%, 35–40%, ca. 40% and 60–70% for loose LR, loose WT, fuel-chips and roundwood, respectively. According to Nylinder *et al.* (2016a), chipping LR and WT can increase payloads by ca. 154 and 61%, respectively. However, there are no robust methods for determining solid volume contents from bulk volumes (Björklund & Fryk 2014), and conversion factors for bulk LR and WT substantially vary, since windrow shapes and raw materials are irregular and heterogeneous. Solid volume contents of pine WT windrows have been determined, from windrow heights and cut-surface diameters of stacked trees (Lindblad *et al.* 2010). Other factors have been presented for converting bulk volume to mass of partly-delimbed energy wood (Nylinder *et al.* 2016b), and bulk to chipped volumes of WT windrows (Laurila & Lauhanen 2012), and both LR and roundwood (Schulmeyer *et al.* 2015). However, conversion factors for bulk forest fuels are not currently used in Sweden and thorough studies, which may be useful for logistic planning (production management) as well as cost-benefit estimates for market players, are needed.

Thus, the main aims of this study were to: describe and compare storage conditions and fuel-chip quality (MC, PSD, AC) of LR and WT windrows, delivered to the same plant by the same supplier during one season; and develop a model for estimating dry mass contents of LR and WT windrows.

Materials and Methods

Study site

From February to April 2014, 44 LR windrows and 32 WT windrows (experimental units) belonging to the Northern Forest Owners' Association (*Norra Skogsägarna*) were inventoried at 34 sites within 80 km of Umeå, northern Sweden (Figure 1). Hereafter, LR refers to tops and branches obtained predominantly from final-fellings of Norway spruce (*Picea abies*), with minor fractions of stemwood of spruce and other species. WT refers to undelimbed small-diameter trees, either harvested at full length (i.e. whole unprocessed trees) or bucked in sections (i.e. unprocessed tree parts), ca. 6–9 m long. Two teams of contractors harvested and forwarded the forest fuel (LR and WT) into windrows. WT was harvested in early thinnings (65% of the sites containing WT) and the rest in clearings of overgrown edges of arable land, roadsides and industrial land. The cut area averaged 5.8 ha (range 0.7–25.2 ha) for sites containing LR and 4.4 ha (range 0.1–17.5 ha) for WT sites.



Site no.	No. of windrows	No. of trucks	Dry t per truck
1	1	5	17.3
2	2	3	15.6
3	3	13	17.1
4	3	6	16.2
5	1	6	14.2
6	1	2	15.3
7	1	2	20.2
8	6	6	16.8
9	6	17	20.6
10	4	4	15.6
11	1	4	22.2
12	2	5	18.9
13	3	8	12.7
14	2	2	8.2
15	1	8	13.9
16	1	3	14.8
17	1	3	9.9
18	2	6	16.2
19	1	3	8.6
20	1	1	11.8
21	1	3	16.5
22	3	4	20.4
23	10	9	16.0
24	2	5	15.8
25	2	2	13.9
26	4	5	16.9
27	1	2	13.7
28	1	2	20.0
29	1	2	18.5
30	1	3	18.0
31	1	3	18.3
32	1	1	7.6
33	1	1	21.9
34	4	10	19.9

Figure 1. Sites (numbers) and windrows (rhombuses or crosses) in the study area. Some windrows close to each other cannot be distinguished at the represented scale. Number of windrows per site, trucks and mean mass (dry t) per truck are shown in the inset table.

Percentages of species (by volume) in LR windrows were estimated visually. The tree species and butt-end diameter (D_{butt}) of every cut surface (with no minimum threshold) that the field researcher could reach at above-ground heights of 0.9–1.6 m in WT windrows were recorded; sampling positions were defined every fourth meter along the front (long) side of each windrow. Photographs of front sides of WT windrows were taken to calculate the relative percentage of cut surfaces. Dimensions of the windrows were then measured as follows. The height of their front side was measured with a stick (measuring the height of their rear sides proved difficult, and was avoided). Their height was measured at least at three points if their shape was approximated as a trapezoidal prism (Figure 2), but only at one point if it was approximated as a triangular or rectangular prism. The length of each windrow's base (and top if trapezoid) was measured along the front side, and width along the left and right sides (levelled out where most tops ended).

Figure 2. Dimension measurements on a windrow approximated to a trapezoidal prism (Eq. 1).

Most windrows were covered by paper (4 m wide, placed on the top-front part of the windrow and reaching the sides) except at sites 5, 16, 20, 26 and 32 (Figure 1). A 5–40 cm snow layer covered all windrows until mid-March. Most LR windrows were placed in the harvesting site and beyond reach of the chipper's crane (Table 1) if operated from the forest road. However, most WT windrows were placed on a roadside or landing, within reach of the chipper's crane. The long side of the surveyed windrows was parallel to the road, when placed by the roadside, and the material was usually organized with cut surfaces pointing toward the road with all stems/tops in the same orientation, facilitating grip and feed-in to the chipper. The preferred underlay for tipping over the chip-bin, snow (Table 1), was often compacted and flattened by the forwarder's front-mounted shovel and crane, with the help of a log. Dates of harvesting, forwarding and chipping were provided by the forest owners' association, while the plant provided dates of fuel-chip deliveries (Figure 3). The average windrowing time before delivery to the plant was 10 months (range 1 to 31 months), and windrows had all been built within 1 month after harvest. Observations of the windrows' exposure to ambient conditions (shading) showed that all sides of 59% were placed away from a forest edge or another windrow (with nothing shading or sheltering them from solar radiation or wind), and at least one side of the other 41% was sheltered by another windrow or forest edge.

Table 1. *Windrow placement and underlay for tipping over the chip-bin.*

Assortment	Placement (%)			Underlay[1] (%)		
	Roadside	Landing	Out of reach	Snow	Clean bare ground	Forest ground
LR	32	2	66	41	7	52
WT	63	28	9	91	3	6

1. Clean bare ground consisted of grass or gravel. Forest ground was an irregular underlay with stumps, undergrowth, moss, mineral soil, etc.

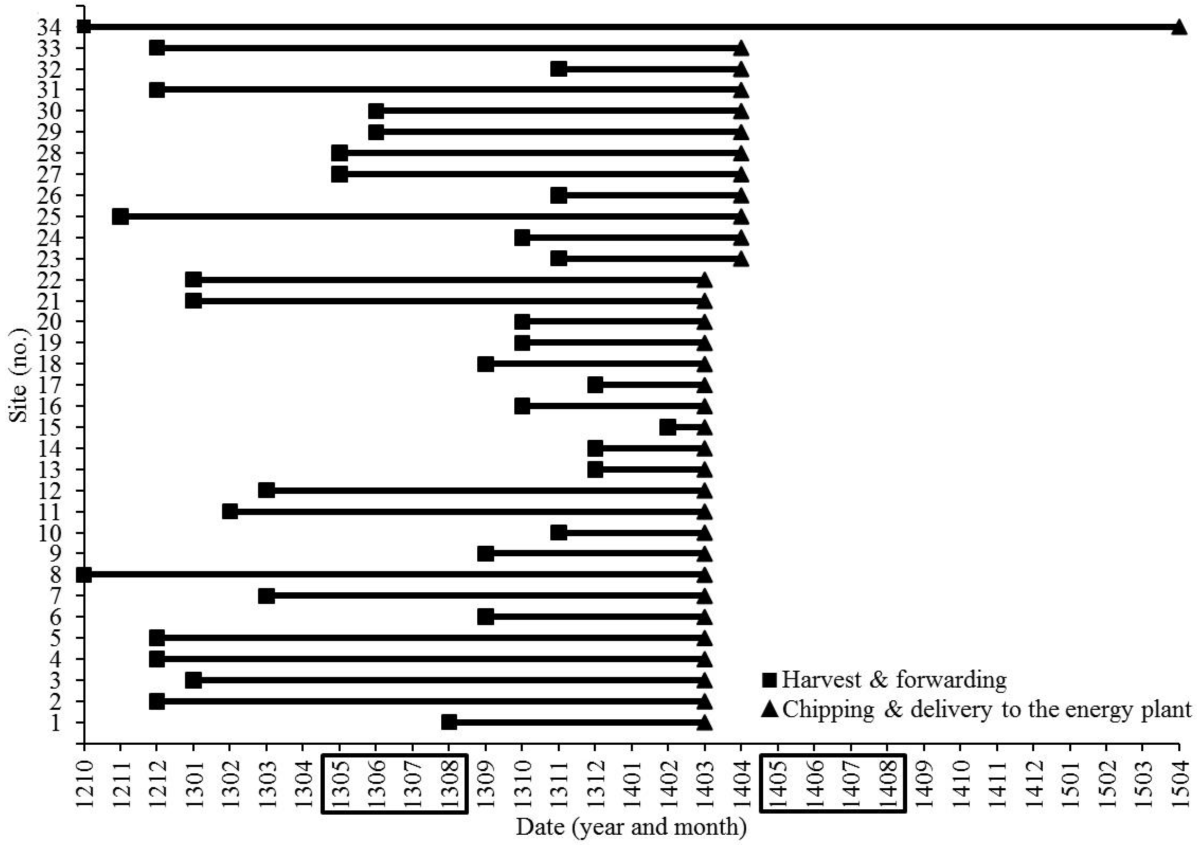


Figure 3. Start (harvest & forwarding) and end (chipping & delivery to the plant) dates of windrow storage at each site. Months favourable for drying (May, June, July and August) are framed.

Windrow chipping and MC determination by the plant

The inventoried windrows were chipped by one of two operators employed by a contractor using a Bruks 805 CT chipper with a self-dumping chip-bin (volume: 21 m^3), mounted on a Komatsu 860.4 forwarder, at the largest target chip length setting (40 mm). The fresh mass of every chip load was registered using an integrated scale in the bin (pre-calibrated by the contractor). Each loaded bin was tipped at the roadside or a landing, and loaded within 2 days into a Volvo FH13 chip-truck with container and trailer (total volume: 122 m^3), self-loading crane (Epsilon Palfinger M110LS97) and bucket halves (HSP Gripen 055). The trucks delivered the fuel-chips to a combined heat and power plant (63°52'6"N, 20°24'34"E) belonging to *Umeå Energi AB* (Figure 1). Each truck was scaled on a static weighbridge (Flint AB, Sweden; two plates, resolution: 20 kg, max. 80 tonnes, calibrated once per year) at the plant weighing station. Since some truckloads were tipped directly into the dump pocket at the plant, the truck driver filled, just before loading at the forest roadside, a 3-litre paper bag with fuel-chip samples from seven points at different levels and depths in the pile, as stipulated by Umeå Energi (2014). MC (wet-basis) was determined by weighing the samples before and after drying at 105±2 °C for 48 h, by the plant, following European Standard EN 14774-2:2009 (CEN 2009a). The truck drivers were trained in the sampling procedures, but personnel from the plant or VMF (Swedish Timber Measurement Council) performed control samplings, as described by VMF Nord (2014), to assess possible deviations. The plant provided a dataset describing (*inter alia*) site, assortment, mass (fresh and dry t), MC and energy content of each chip-truck load in the trials.

Fuel-chip sampling during fieldwork and quality assessment

Fuel-chips were sampled from 25 covered windrows (10 LR and 15 WT) at 16 sites (predetermined as the chipper's route was pre-planned by the forest owner's association) within a few hours of the chipper tipping them onto the ground. The numbers of samples per windrow (range 1–3) and windrows sampled per site (range 1–4) depended on the windrow size and total number, and time available before the trucks started loading the chips. During sampling, a 5-litre bucket was filled with 5–8 subsamples shovelled from different points and heights of the chip pile (digging at least 10 cm inside). The MC, PSD and AC of each collected sample (46 in total) were determined. MC was determined following EN 14774-2:2009 (24 h). To calculate PSD, the same (dry) samples were then subjected to a 15-min pre-defined program in an electromagnetic sieve shaker (BA 400N, CISA, Spain) with oscillating circular sieves (opening sizes: 63, 45, 31.5, 16, 8 and 3.15 mm). The seven fractions were weighed to determine percentages of dry mass associated with each particle size class, then pooled and milled with a cutting mill, initially with a 6-mm sieve and subsequently with a 1-mm sieve to accelerate the milling. Each milled sample was subdivided with a riffle box, to obtain a 0.5-litre subsample from which two ~2 g subsamples were used for AC determination (% of dry mass of the entire sample), following EN 14775:2009 (CEN 2009b).

Analyses

Statistical analyses were performed using Minitab 16 and R 0.99 (R Core Team 2015), deeming results to be significant if $p < 0.05$.

Comparison of fuel-chip quality parameters and correlations

Quality parameters (MC, PSD, AC) of fuel-chips were compared by one-way ANOVA with Tukey post-hoc tests. Four groups of study sites (designated G1, G2, G3 and G4) with homogeneous characteristics (with/without fieldwork sampling, covered/uncovered windrows, and source of MC measurements: field/plant) were defined, as shown in Table 2, and measurements within each group were pooled. We then compared: LR vs. WT fuel-chip samples of G1 and G2, separately (Comparison 1), to identify possible assortment-based differences in MC; G1 vs. G2 of each assortment (LR and WT, separately), to identify sampling-method (field vs. plant)-based differences in MC (Comparison 2); and LR vs. WT fuel-chip samples of G3 and G4 (Comparisons 3 and 4, respectively). The PSD values (fractions of <3.15, 3.15–8, 8–16, 16–31.5, 31.5–45, 45–63 and >63 mm particles) associated with different assortments in G1 were compared (LR vs. WT). AC values associated with different assortments in G1 were also compared (LR vs. WT). Correlations between shares of fines (% of dry mass with particle size <3.15 mm) and both MC and AC of LR and WT (separately and together), were examined by calculating Spearman's rank-order correlation coefficients (rho).

Table 2. *Groups of sites for comparison of MC.*

Group	Site numbers	Source of MC measurements
G1	1, 3, 8-15, 19, 21, 23, 24, 29, 30 (with fieldwork sampling and covered)	Fieldwork (also AC and PSD)
G2	1, 3, 8-15, 19, 21, 23, 24, 29, 30 (with fieldwork sampling and covered)	Energy plant
G3	1-4, 6-15, 17-19, 21-25, 27-31, 33, 34 (with/without fieldwork sampling and covered).	Energy plant
G4	1 to 34 (all sites: with/without fieldwork sampling and covered/uncovered)	Energy plant

Windrow bulk densities and models for predicting dry mass content

The fresh (raw) and dry bulk density of each LR and WT windrow were calculated in terms of fresh mass and dry mass per bulk cubic metre (m^3). In addition, the windrows' bulk volumes were calculated using the measured lengths, heights and widths. The geometrical shape of each windrow was approximated as a trapezoidal (Eq. 1, Figure 2), triangular (Eq. 2) or rectangular prism (Eq. 3), expressing volume as:

$$Vol_{trapezoidal\ prism} = \frac{(length_{base} + length_{top})}{2} \times \frac{(height_1 + height_2 + height_3)}{3} \times \frac{(width_{left} + width_{right})}{2} \quad (1.)$$

$$Vol_{triangular\ prism} = \frac{length_{base}}{2} \times height \times \frac{(width_{left} + width_{right})}{2} \quad (2.)$$

$$Vol_{rectangular\ prism} = length_{base} \times height \times \frac{(width_{left} + width_{right})}{2} \quad (3.)$$

The fresh mass and dry mass of each windrow were calculated by two approaches. In the first (referred to as "chipper"), registered fresh masses from the chipper and calculated dry masses were used, with MC values obtained from fieldwork sampling (when available). For windrows not sampled in the field, a weighted average MC based on the plant measurements (Figure 4) was assumed for all windrows within the same site. In the second approach (referred to as "plant") only data from the plant (fresh masses and MC) were used. However, fresh masses from the plant were provided for truckloads (not individual windrows), so the fresh mass of each windrow was estimated, as follows. Bulk volumes of all windrows in each site were summed, then percentage contributions of each windrow were calculated and multiplied by the total fresh mass delivered from the site (i.e. total mass of all truckloads), yielding a theoretical windrow fresh mass. Dry mass was calculated using the weighted average MC of material delivered from the site (Figure 4).

Differences in bulk density between assortments (LR vs. WT), obtained using the same type of data (chipper or plant) and type of density (raw or dry) were tested by one-way ANOVA, as well differences between bulk densities (raw and dry) of the same assortments calculated using different types of data (chipper vs. plant). Linear regression was used to test the dependence of dry bulk densities of LR on storage time, and dry bulk densities of WT on storage time, share of cut surfaces and D_{butt}. Linear regression models were also constructed for predicting the dependence of windrows' dry mass (dry t, dependent variable) on their bulk volume (m^3, independent variable). Separate models were developed for each assortment using both calculation approaches (chipper and plant data), and the quality of the models was compared using Akaike's Information Criterion.

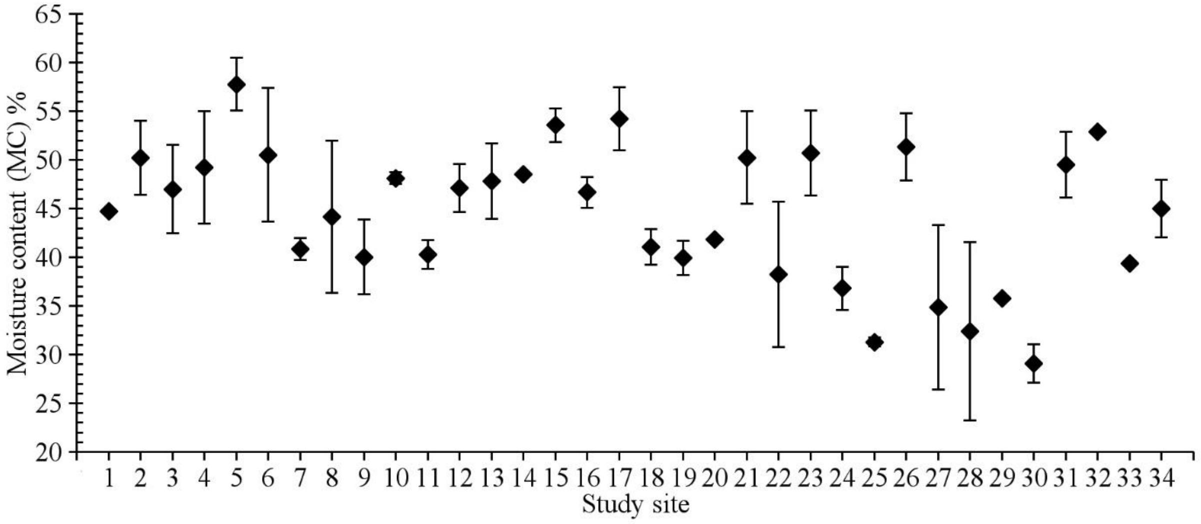


Figure 4. Intra-site mean MC (weighted by the fresh mass of fuel-chip loads in the trucks) and standard deviation (SD) of MC measurements.

Other analyses

Effects of some storage conditions on MC

The dependence of the windrows' MC on their exposure (shading) to solar radiation and wind was tested with one-way ANOVA by assessing differences between windrows for which: (i) all sides were located away from a forest edge or another windrow (so nothing was shading or sheltering them from solar radiation or wind), and (ii) at least one side was shaded by another windrow or forest edge. The dependence of the plant-determined MC on the number of "drying months" (May, June, July, August, when MC typically decreases in northern latitudes) the windrows were seasoned (Figures 3 and 4) was also tested by one-way ANOVA. LR and WT fuel-chip samples of G3 (covered windrows) were considered (separately and together) in these analyses.

Effect of chip-truck load size on intra-site MC variation

Regression analyses were applied to test if the intra-site standard deviation (SD) of MC measurements of fuel-chips at the plant (Figure 4) increased with increases in average load size (dry t per truck; Figure 1), or decreased with increases in number of truckloads per site. The variation in the average load size resulted from trucks being partially loaded and variation in MC, and thus the amount of dry mass represented by the single sample taken for MC determination at the plant.

Effects of cut surface area and other variables on AC

The cut surface percentage of the total front (long side) area of each WT windrow was determined from photographs using Adobe Photoshop CS6 by manually selecting the visible cut surfaces within a 1000×1000-pixel region in the centre of the picture (analysing one photograph per windrow). We expected windrows containing large trees to yield lower AC than smaller trees, and tested the hypothesis by regressing AC of WT windrows against their calculated percentage of cut surfaces, average D_{butt}, and dry bulk density.

Results

A total bulk volume of 42 298 m^3 was measured in the field, averaging 557 bulk m^3 per windrow (range 72–1729 bulk m^3) (Table 3). A total fuel-chip dry mass of 2651 dry t, corresponding to a total energy content of 12 940 MWh, was scaled at the plant. The chipper registered 719 full loads, averaging 3.9 and 3.4 dry t for LR and WT, respectively. Chip-trucks delivered 159 loads to the plant, with an average mass per load of 17.3 dry t for LR (range 3.6–24.9 dry t) and 15.6 dry t for WT (range 3.7–23.9 dry t). The overall average D_{butt} for WT was 11.3 cm (average stem solid volume:~60 litres, depending on tree species, Table 4). The cut surface area accounted for, on average, 18.7% (range 6.8–36.2%) of the total front side area of WT windrows.

Table 3. *Average characteristics of surveyed windrows (n=no. of windrows, SD in parentheses).*

Assortment	*n*	Base length (m)	Height (m)	Width (m)	Bulk volume (m^3)	Dry mass[1] (dry t)	Total wet mass (fresh t)		Total dry mass (dry t)	
							Chipper[1]	Plant[2]	Chipper[1]	Plant[2]
LR	44	31.0 (18.1)	3.3 (0.5)	6.5 (0.9)	545 (399)	37 (26)	3015	3248	1620	1763
WT	32	23.0 (12.9)	3.6 (0.9)	8.8 (1.4)	572 (441)	33 (26)	1957	1620	1041	888
LR+WT	76	-	-	-	557 (415)	35 (26)	4972	4868	2661	2651

1. Fresh masses from the chipper and MC measurements from the fieldwork when available, otherwise from the plant. Using only MC values from the plant yielded 1.7% higher dry mass content.
2. Fresh masses and MC values from the plant.

Table 4. *Average tree species distribution (%) and D_{butt} (cm, basal-area weighted, SD in parentheses).*

Assortment	Species											
	Norway spruce (*Picea abies)*		Scots pine (*Pinus sylvestris*)		Birch (*Betula* spp.)		Grey alder (*Alnus incana*)		Willow (*Salix* spp.)		Aspen (*Populus tremula*)	
	%	D_{butt}	%	D_{butt}	%	D_{butt}	%	D_{butt}	%	D_{butt}	%	D_{butt}
LR	60 (29)	-	17 (24)	-	16 (15)	-	4 (10)	-	1 (3)	-	2 (6)	-
WT	14 (17)	10.8 (4.6)	2 (4)	9.7 (2.7)	30 (19)	11.1 (3.1)	41 (29)	10.8 (4.8)	12 (15)	13.7 (4.7)	1 (2)	11.9 (4.5)

Comparison of fuel-chip quality parameters and correlations

The overall mean plant-determined MC was 45% (range 26–61%), with fairly similar mean values among groups and assortments (Table 5). Comparisons of mean MC values revealed that the MC associated with specific assortments or sampling methods did not significantly differ (Table 6). However, MC varied more in LR than in WT (Table 5), and varied substantially both between and within sites (Figure 4). The calculated inter- and mean intra-site SDs of MC measurements were 7.1% and 3.4%, respectively. LR yielded ca. two-fold significantly higher proportions of fines and oversized fractions than WT (12.2 vs. 5.8% and 2.2 vs. 1.1%, respectively) (Table 7), and significantly ($p<0.001$) higher AC (mean 2.43%, SD 0.49%, range 1.67–3.44%) than WT (mean 1.54%, SD 0.56%, range 0.56–2.93%). Furthermore, fines were positively correlated with MC in LR (rho=0.592, p=0.016), WT (rho=0.378, p=0.040) and both assortments together (rho=0.375, p=0.010). Fines were also positively correlated with AC in LR (rho=0.605, p=0.013) and both assortments (rho=0.539, p<0.001), but not with WT alone (rho=0.048, p=0.800).

Table 5. *Arithmetic mean MC for groups and assortments. n=no. of samples (or chip-truck deliveries) and SD in parentheses.*

	Groups							
	G1		G2		G3		G4	
Assortment	*n*	MC (%)	*n*	MC (%)	*n*	MC (%)	*n*	MC (%)
LR	16	47.2 (9.4)	45	45.2 (7.2)	93	44.3 (7.3)	102	45.3 (7.8)
WT	30	45.0 (6.6)	58	44.3 (6.4)	50	44.8 (6.5)	57	45.4 (6.3)
LR+WT	46	45.8 (7.8)	103	44.7 (6.7)	143	44.5 (7.0)	159	45.3 (7.2)

Table 6. *Results from comparisons of MC among groups and assortments.*

Comparison	Sequence in Table 5	Group	Assortment	*p*
1	column-wise	G1	LR vs. WT	0.372
1	column-wise	G2	LR vs. WT	0.503
2	row-wise	G1 vs. G2	LR	0.387
2	row-wise	G1 vs. G2	WT	0.609
3	column-wise	G3	LR vs. WT	0.663
4	column-wise	G4	LR vs. WT	0.932

Table 7. *Average PSD (% of dry mass) of fieldwork-sampled windrows (G1). Different superscript lowercase letters indicate significant differences ($p < 0.05$) between assortments (column-wise) and SD (%) in parentheses.*

Assortment	*n*	Particle size class (mm)						
		<3.15	3.15<8	8<16	16<31.5	31.5<45	45<63	63<
LR	16	12.2 ^{a} (4.3)	20.0 ^{a} (3.5)	14.8 ^{a} (7.2)	40.6 ^{a} (11.5)	6. 5 ^{a} (2.7)	3.7 ^{a} (2.4)	2.2 ^{a} (1.6)
WT	30	5.8 ^{b} (1.8)	11.0 ^{b} (3.6)	15.0 ^{a} (6.5)	55.9 ^{b} (8.7)	8.3 ^{a} (4.3)	2.9 ^{a} (2.9)	1.1 ^{b} (1.2)

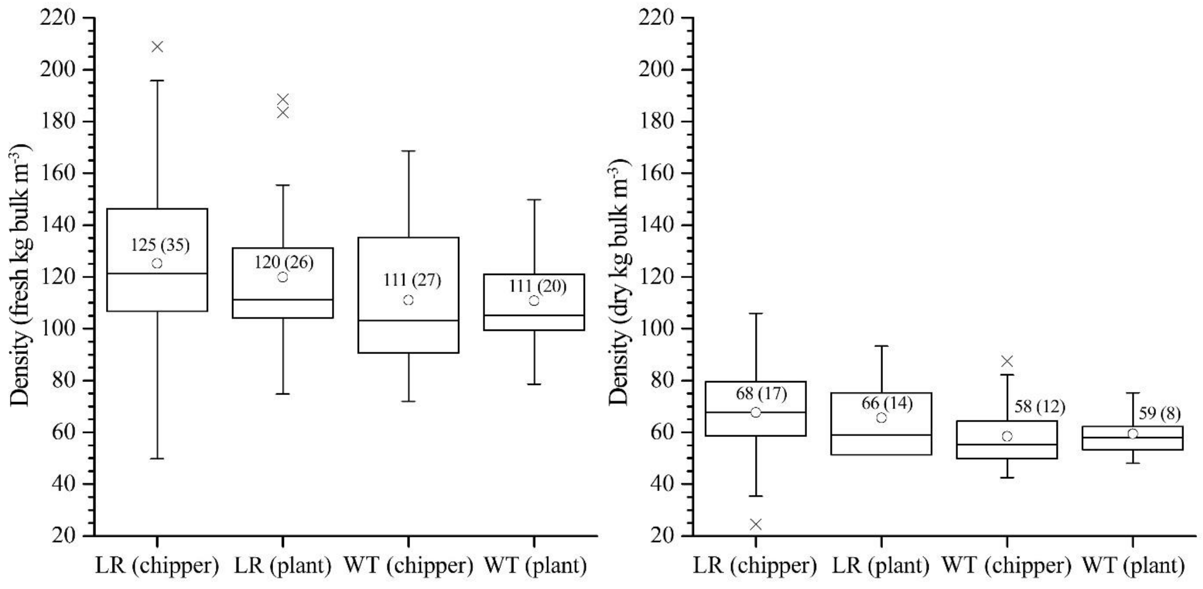


Figure 5. Box-and-whisker plots of fresh (left) and dry (right) bulk densities of LR and WT windrows calculated using chipper and plant data. Circles and horizontal lines inside the plots indicate arithmetic means (SD in parentheses) and medians, respectively.

Windrow bulk densities and models for predicting dry mass content

Measured densities (Figure 5) of LR and WT averaged 68-66 and 58-59 dry kg bulk m^{-3}, respectively, depending on whether chipper or plant data were used. Fresh bulk densities calculated using the same approach did not differ significantly between assortments (LR vs. WT; p=0.062, and 0.099 for chipper and plant data, respectively). However, dry bulk densities did significantly differ between LR and WT (p=0.012, and 0.024 for chipper and plant data, respectively). Fresh bulk densities of the same assortment calculated using chipper and plant data did not significantly differ (p=0.427, and 0.954 for LR and WT, respectively), and neither did their dry bulk densities (p=0.526, and 0.718 for LR and WT, respectively), although use of chipper data yielded a larger spread than the plant data. Regression analyses (Table 8) showed that dry bulk densities of LR and WT were not dependent on storage time, and dry bulk density of WT was not dependent on the share of cut surfaces or D_{butt}. However, regression analyses showed that the dry mass of the windrows strongly depended on the measured bulk volumes at the roadside and provided four predictive models (Figure 6): one for each permutation of dry mass of LR or WT based on chipper data or plant data. The Akaike's Information Criterion values were lower when plant data (models 2 and 4) were used rather than chipper data (models 1 and 3): 287 vs. 320 and 189 vs. 219, for LR and WT, respectively. Thus, plant data provided higher quality models.

Table 8. *Summary of linear models in R.*

Dependent variable	Independent variable	*p*	R^2(adj)
dry bulk density LR	storage time	0.956	0
dry bulk density WT	storage time	0.231	0.016
dry bulk density WT	cut surface area	0.283	0.006
dry bulk density WT	D_{butt}	0.321	0.001
windrow's dry mass content	bulk volume	Figure 6	Figure 6
SD of MC measurements	mean load size	0.298	0.004
SD of MC measurements	number of trucks	0.731	0
AC (WT)	cut surface area	0.166	0.076
AC (WT)	D_{butt}	0.434	0
AC (WT)	dry bulk density WT	0.367	0

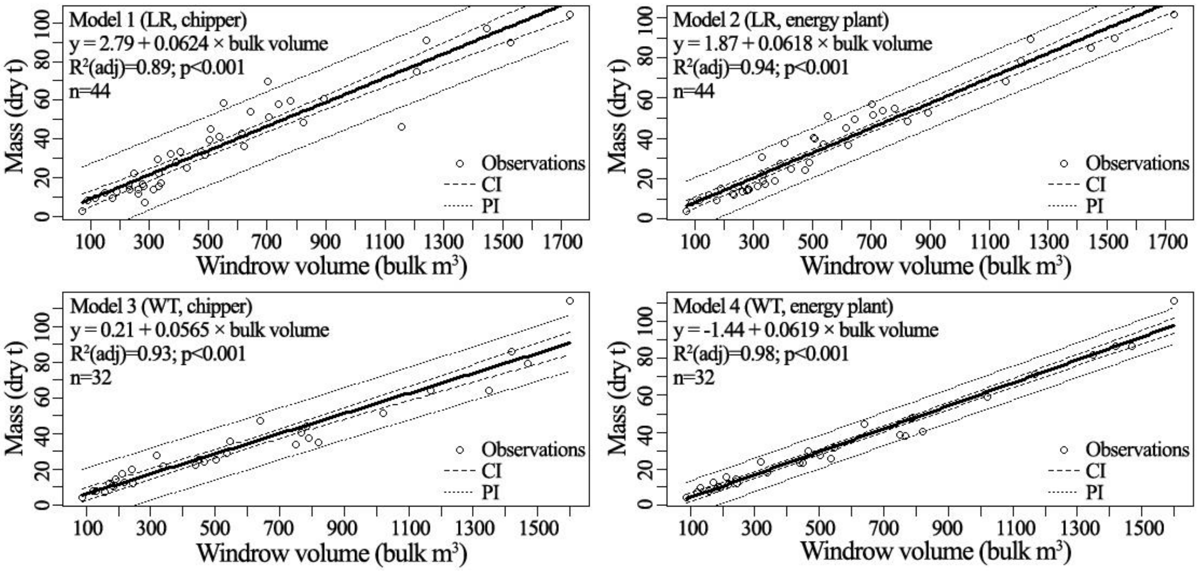


Figure 6. Models for predicting the mass (dry t) of LR and WT windrows, using fresh mass measurements from the chipper and MC from the fieldwork when possible (models 1 and 3), or using only data from the plant (models 2 and 4). Confidence intervals (CI) and prediction intervals (PI) are represented by dashed lines and dotted lines (95% confidence level), respectively.

Other analyses

Fully exposed LR windrows (with no shading or shelter from solar radiation or wind) had a significantly 6.7% lower mean MC (p=0.005) than sheltered counterparts (43.3 vs. 50.0%, respectively). Results were not conclusive for WT alone (p=0.595), but pooled data showed that fully exposed LR and WT windrows also had a significantly 3.3% lower (p=0.022) mean MC than sheltered counterparts (43.4 vs. 46.7%, respectively). LR windrows seasoned for at least one drying period had a significantly 5.7% lower mean MC (p=0.002) than those that were not seasoned in the drying months (43.1 vs. 48.8%, respectively; Table 9). Most WT windrows were not seasoned during the drying period (May-August). Regression analyses did not detect any significant association between intra-site SD of MC measurements and either average load size or number of truckloads per site. Similarly, no significant associations were found between the AC of WT windrows and their percentage of cut surfaces, average D_{butt}, or dry bulk densities (Table 8).

Table 9. *Arithmetic mean MC for covered windrows (G3) and total number of drying months (0, 1, 3, 4, 5 or 8). Different subscript uppercase letters indicate significant differences in MC between factors (number of drying months) in the same assortment (row-wise).*

			Number of drying months (May, June, July, August) seasoned											
			0		1		3		4		5		8	
Assortment	*p*	R^2(adj)	*n*	MC (%)	*n*	MC (%)	*n*	MC (%)	*n*	MC (%)	*n*	MC (%)	*n*	MC (%)
LR	0.002	0.290	15	48.8_{A}	-	-	2	32.4_{B}	20	43.1_{B}	1	39.4_{AB}	4	45.0_{AB}
WT	0.979	0	21	44.7_{A}	1	44.8_{A}	-	-	4	44.2_{A}	-	-	-	-
LR+WT	0.011	0.146	36	46.4_{A}	1	44.8_{AB}	2	32.4_{B}	24	43.3_{AB}	1	39.4_{AB}	4	45.0_{AB}

Discussion

Main results

This study consisted of a large survey of several characteristics of LR and WT windrows without a defined experimental design. The high diversity of sites and variation in storage conditions hindered multivariate statistical analyses, so analysis was restricted to the descriptive statistics, regression analyses, ANOVA and post hoc tests of measured variables described in the preceding section.

Mean bulk volumes and heights of LR and WT windrows were similar, but LR windrows had ~8 m longer bases, and WT windrows were ~2 m wider (Table 3). The bulk volumes were calculated using general formulae, which only approximated the real shapes. Other formulae or photogrammetric techniques could be used for volume determination. To minimize the cover cost and maximize the cover effect, the windrow height should be maximized (Björheden *et al.* 2013). Most LR windrows were fully covered by the paper, so large quantities of snow were retained, but substantial parts of the wider WT windrows' surface remained uncovered. The paper on the WT windrows stored since autumn 2012 was severely degraded. Therefore, use of wide paper (6 m) for WT and windrowing only for the useful life-time of the paper are suggested. Covering the windrows is a cost-effective method for improving fuel-chip quality, as Jirjis *et al.* (1989) and Nurmi & Hillebrand (2007) found that covered LR and WT windrows had 8–10% and 3–6% lower MC, respectively, than uncovered counterparts.

The total mass measured by the chip-bin scale was ~2% larger (104 fresh t) than the total mass measured by the truck weighbridge at the plant (Table 3). Some material may have spilled when the chips were loaded into trucks and some water may have evaporated before the chips were scaled at the plant. However, relative differences in fresh mass measurements of chips at individual sites between the chip-bin scale and plant weighbridge ranged between -19 and +14%. Thus, other (unknown) factors must strongly contribute to these differences in measured masses. In this respect, it should be noted that readings from the chip-bin scale (typically used to avoid overloading of small trucks) are only indicative according to the chipper manufacturer, and some may have been incorrectly manually registered. In contrast, the weighbridge at the plant is frequently calibrated, and its measurements are used to calculate payments, so it is more reliable.

Lack of space, low-hanging power line conductors, differences in terrain elevation or a ditch seemed to be reasons to place windrows far from the roadside in some sites (Table 1), but no apparent reasons were found in other sites. Longer terrain driving during forwarding of the forest fuel into windrows would have reduced terrain driving for the chipper (which always discharged the chip-bin by the roadside/landing) and increased chipper utilization rates, lowering total supply costs. Attempts were made to avoid overturning the chip-bin on bare forest ground, which increases risks of contamination and material losses during fuel-chip loading onto trucks.

Moisture content (MC)

The grand mean MC was 45% (Table 5), which is appropriate as the combustion technology at the plant (circulating fluidized bed) functions best when the MC of combusted material is 40-55%, as the flue gas condenser then has maximal effect. Procedures and amounts of sampled material differed significantly between the fieldwork and plant sampling methods. With the plant method, samples were taken from whole fuel-chip piles, and were considered more representative of the entire site. Due to the numerous sites, and needs to inventory the windrows before chipping and adapt to the route of the chipper, use of a standard sampling method, such as EN 14778:2011 (CEN 2011), during fieldwork would have been impractical. For comparison of sampling methodology, comparing individual sites (rather than considering all sites together) would have been more convenient, but this was prevented by the impossibility (in most cases) of linking specific windrows to specific chip-truck loads.

The inter- and intra-site SDs of MC measurements (7.1% and 3.4%, respectively) were relatively large (Figure 4). However, very similar average SDs (7.0 and 3.5%, respectively) have been reported by Björklund & Eriksson (2013), who noted that numbers of samples per truck should be inversely related to the number of trucks from a site to fulfil the accuracy requirements of the Swedish Forest Agency. MC will also vary within truckloads, e.g. Nilsson *et al.* (2012) and Björklund & Eriksson (2013) found average SDs of 2.6% and 5.0% within loads, respectively. We have no corresponding values for comparisons, because this variation was not examined in our trials. Representative sampling is particularly important financially for forest owners delivering small volumes occasionally. In contrast, a forest company delivering large volumes yearly will receive payment for an average MC in the long run. In our study, one sample per truck was taken, regardless of the number of truckloads per site. We expected intra-site SD to increase with increases in average load size (and thus the dry mass represented by the single sample) and decrease with increases in number of truckloads, but the results did not support these hypotheses (Table 8). Some variation in MC within and between sites may also have been due to precipitation during chipping, as snow/rain will rapidly penetrate fuel-chip piles, increasing MC in the truckload. The observed spread in MC among fuel-chip deliveries poses challenges (e.g. maximization of boiler efficiency) for plant managers. Therefore, techniques for on-line measurement of fuel-chip quality parameters and improving information flows along the supply chain must be further developed (Fernandez-Lacruz & Bergström 2016; Fridh *et al.* 2017). Dry mass losses in windrows due to microbial activity and needle loss were not measured in this study, but those too are expected to be lower than in comminuted materials (Lehtikangas 1999), e.g. losses from 0.2-1% and 0.6% per month in LR windrows have been reported by Jirjis and Lehtikangas (1993) and Nurmi (1999), respectively.

Particle size distribution (PSD)

In accordance with previous findings (Nordhagen 2014; Kons *et al.* 2015), proportions of fines and oversized fractions were two-fold higher in LR chips than in WT chips (Table 7), presumably due to LR's larger contents of needles, bark, small twigs and branches. Field samples were taken in a randomized manner, at different times of day. Therefore, some samples were collected with recently sharpened chipper knives and others with worn knives. Thus, blade wear effects on PSD were assumed to be evenly distributed. Nati *et al.* (2010) and Eliasson *et al.* (2011) found that blade wear increased amounts of oversized fractions. Chipping excessively dry or frozen material can lead to increased proportions of fines (Lehtikangas 1999), but as noted by Nati *et al.* (2014) and Spinelli *et al.* (2013), proportions of fines are also influenced by the feedstock and equipment. Screening technologies could allow improved use of different particle sizes. For example, fines (which are ash-rich) could be used in biorefinery or potting-soil industries, medium-sized fractions for torrefaction, pelletization or combustion, and coarse fractions for further chipping/shredding. Fractionation can be combined with wind shifting to reduce amounts of impurities (e.g. stones). The resulting improvements in feedstock quality and logistic efficiency, together with reductions in risks of failure in the feeding systems and damage at end-user facilities could compensate for the extra costs of such systems.

Ash content (AC)

In accordance with Pettersson & Nordfjell (2007), the AC was higher in LR (2.4%) than in WT (1.5%), but its SD was also larger in WT, and some WT samples had similar AC to LR. This may have resulted from variations in WT windrows' stemwood content. We expected WT windrows containing large trees to yield lower AC than smaller trees, but the results did not support the hypothesis (Table 8). Limitations in measurements of D_{butt} and calculation of cut surfaces may have been partly responsible for this, since some surfaces were unreachable or un-exposed as they may have been covered by snow or shaded by another stem or hanging branches. Furthermore, crisscrossing and protruding stems could have increased the error. D_{butt} could also be determined from harvester production files, but these files were not available in this study. Attempts to measure the diameter and solid volume of material in multi-tree harvester/felling heads used for WT (which is more difficult than measuring material in single-grip heads) are currently underway.

Contaminating ash may also have contributed to the relatively high AC. Accordingly, pictures and field observations revealed that some windrows contained small uprooted trees (with mineral soil and stones attached), perhaps resulting from use of a roundwood (rather than open) grapple or insufficiently careful working methods. Although other windrows seemed impurity-free, pollutants could have been present in the non-examined parts and their presence is more difficult to evaluate in LR than in WT. Thus, despite the cautious work, some impurity-containing biomass may have been fed-in to the chipper (particularly, for example, during night-time work). Holistic supply-chain planning and good communication between the links are needed, since low-quality work in the initial stages may result in low chipping productivity (as the operator will have to sort the material and change blades often) and quality. Pre-clearing is therefore recommended (Eliasson & Johannesson 2009). Other sources of contamination could include dust from nearby roads. However, this was difficult to evaluate since most windrows were placed by roadsides with little traffic, and some windrows far from roadsides also exhibited high AC.

Correlations between fuel-chip quality parameters

The detected positive correlations between fines and both MC and AC have been previously reported for LR, by authors who defined fines as <5 mm particles, rather than <3.15 mm particles (Jirjis *et al.* 1989; Jirjis & Lehtikangas 1993; Lehtikangas & Jirjis 1993, 1995). Fines absorb more air moisture than other fractions, thereby reducing air movement within windrows and retarding drying. Nylinder & Thörnqvist (1980) found that fines can have 30% higher MC than stemwood, and Lehtikangas (1999) that moist LR readily binds small particles (such as sand), thereby raising AC. Moreover, Hakkila (1989) found most AC in fine fractions, because the mineral content is highest in components with high metabolic activity, such as needles. Kons *et al.* (2015) confirmed that fine fractions of both LR and WT have the highest AC of all size classes.

Windrow bulk densities and prediction models

Bulk density differed among windrows within the same site according to chipper data, but not according to plant data, at least partly explaining the relatively large SD associated with the chipper data (Figure 5). Results showed that dry bulk densities of LR and WT were not dependent on storage time, and dry bulk densities of WT were not dependent on the share of cut surfaces or D_{butt} either (Table 8). The densities were probably affected by the harvest technology and handling during forwarding, but these hypotheses require validation. LR windrows seemed more densely packed (easier to compress) than many WT windrows, possibly explaining the higher (12–17%) bulk density of LR. Furthermore, most LR windrows contained varying amounts of stemwood (small trees), helping to level-out differences with WT. Cutting technologies for rough-delimbing and compressing tree bunches increase payloads and transport efficiency of WT (Bergström & Di Fulvio 2014).

Chipper data also yielded prediction models with wider confidence and prediction intervals than plant data (Figure 6). Therefore, models 2 and 4 are probably more reliable for LR and WT than models 1 and 3, respectively, as they were based on weighbridge measurements. They also had higher quality according to Akaike's Information Criterion. Moreover, the relative effect of uncertainty (range of variation of the model's output) decreases with increasing windrow bulk volume. Models should be rapidly implemented by forest practitioners, using simple formulae to calculate bulk volumes. When a bulk volume is entered, the models will return mean dry mass of the windrow and confidence and prediction intervals, showing ranges of possible mean values and all possible single values, respectively. However, models should only be used within the range of bulk volumes observed during fieldwork (range 72–1729 bulk m^3). Rather than serving as a basis for payment, prediction models can be useful for logistic planning (e.g. chipper routes, required comminution times and truck requirements) and rough economic estimates within given confidence levels, thereby improving the efficiency of resource allocation. The dry mass models generated in our study could be used together with models for forecasting MC (Routa *et al.* 2015; Eriksson *et al.* 2017) and estimating energy content in LR/WT windrows.

In conclusion, this study provides information on the characteristics of windrows and their variations in northern Sweden, which are probably representative of windrows in other locations in Fennoscandia with similar supply chains. Further development of techniques for accurately measuring bulk volumes and quality parameters of uncomminuted and comminuted forest fuels is required. Fuel-chips from WT had higher quality than LR (less ash, fines and oversized fractions) for the considered end-use, but quality requirements will vary in the coming bioeconomy. Due to the large spread in windrow bulk densities, the use of prediction models for bulk forest fuels should be restricted to logistic planning (production management) to increase efficiency of forest fuel supply chains. The results confirm that holistic supply chain management, from the harvesting site to the end-user, is crucial for cost-effective delivery of high-quality residual forest biomasses.

Disclosure statement

No potential conflict of interest was reported by the authors.

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