Monitoring moisture and inorganic content of forest harvesting residues for energy production purposes: A case study

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ABSTRACT

Forest harvesting residues are potentially a vast source of feedstock for bio-based energy facilities. However, the high moisture content of the residues lowers the energy density and adversely impacts the efficiency of transportation. Inorganic and ash contents of forest harvesting residues could also reduce the efficiency of combustion processes and cause fouling, slagging, and corrosion in forest residue-burning apparatuses. The main objective of this research was to conduct measurements to monitor moisture, ash, and inorganic (Ca, K, Mg) contents of forest harvesting residues throughout the year. This would help to decide the optimum size of the residue, height and orientation of the residue pile, as well as the optimum season (that is when those contents are at their lowest) to remove the residues from the forest to biomass-based facilities. Samples of aspen and pine residues, together with temperature, humidity, and precipitation measurements, were taken bi-weekly in two sites at Cynthia and Drayton Valley, Alberta, Canada, from early spring to early fall, and analyzed for two successive years. The results suggest mainly small-size residues should be stored in toll piles until late September, and the piles of such residues should be oriented southward before removing them from the forest.

RÉSUMÉ

Les résidus de coupes forestières sont potentiellement une grande source d'intrants pour les centrales de bioénergie. Toutefois, la teneur en eau élevée des résidus diminue la densité énergétique du produit et affecte négativement l'efficacité du transport. Les contenus inorganiques et en cendre des résidus de coupes forestières peuvent aussi réduire l'efficacité des processus de combustion et causer l'encrassage, la scorification et la corrosion des appareils d'incinération de ces résidus. Le principal objectif de ce projet est de réaliser des mesures expérimentales pour évaluer la teneur en eau, les contenus en cendre et en composants inorganiques (Ca, K, Mg) des résidus de coupes forestières durant l'année. Ceci aidera à déterminer les paramètres optimaux pour l'utilisation des résidus dans les centrales de bioénergie : la taille des résidus, la hauteur et l'orientation des piles de résidus accumulés en forêt ainsi que la saison durant laquelle faire le transport aux centrales est préférable. Pendant deux années, des échantillons de résidus de trembles et de pins, ainsi que des mesures de température, d'humidité et de précipitations ont été recueillis deux fois par semaine à partir du début du printemps jusqu'à tôt à l'automne, et ces échantillons ont été analysés. Les résultats indiquent que les résidus, principalement de petites tailles, devraient être entreposés en forêt en piles hautes et orientées vers le sud pour être ensuite transportés aux centrales tard en Septembre.

KEYWORDS

Forest harvesting residue; bioenergy; biomass transportation; ash content; inorganic content; moisture content

MOTS CLÉS

Résidus de coupes forestières, bioénergie, transport de biomasse, contenu en cendre, contenu inorganique, teneur en eau

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INTRODUCTION

Forest harvesting residues, the main source of three sources of forest residues (Röser et al. 2008), are the by-products of forest management activities not used in traditional wood-processing industries. This non-merchantable woody biomass forms 30-35% of forest-based biomass (Karjalainen et al. 2004). Forest harvesting residues are receiving increased attention as a potentially renewable resource for bioenergy systems (Chum et al. 2011) due to the declining market for paper products, an unsustainable supply of fossil fuels, and global concerns around climate change. In Canada, in 2015, of 721,363 ha of provincial, private, and federal forests harvested, 158 Mm^3 of Roundwood was produced (National Forestry Database, 2015). This left approximately 16.6 to 27.2 Mt of forest harvest residues, considering residue-generation rates from 15 to 25% of the total forest harvest (Kumar et al. 2003; Mabee et al. 2006), the average wood specific gravity of 0.7, and average moisture content of 50%. This residue mainly includes biomass from thinning, harvesting residues (tops, branches, and foliage left on the forest floor or at the roadside), non-commercial species, and – in some jurisdictions – even stumps (Pare et al. 2011). Following the approach used by Bouchard et al. (2013), the total annual potential of producing energy using Canada's forest harvest residue is estimated to be 1,300 to 2,100 MW electric energy and 3,100 to 5,100 MW thermal energy. Moreover, based on an estimation by Mabee et al. (Mabee et al. 2006), this (green) residue can potentially produce a minimum of 1.99 to 3.26 $\times 10^9$ L ethanol per year. However, this vast potential is not exploited by the Canadian energy sector; rather, it is predominantly burned on site (Belart et al. 2017; Brown et al. 2013) with a high probability of causing wildfires and air pollution. Considering its vast potential, researchers have recently been looking into the feasibility of removing forest harvesting residues from the forest and transporting to bioenergy production facilities.

Several researchers investigated the availability of forest harvesting residues and the economic feasibility of removing the residues from the forest for bioenergy production purposes. Jones et al. (2013) analyzed the financial feasibility of various scenarios of delivering forest harvesting residues to a bioenergy plant in western Montana; Scarlat et al. (2011) assessed the availability of residues generated from forestry operations for bioenergy production in Romania; and Ghaffariyan et al. (2013) investigated the economic impact of the five operational factors in the forest residue supply chain – energy demand, moisture content, interest rate, transport distance, and truck payload – in Western Australia.

Besides economic issues, other technical parameters impact the feasibility of delivering forest harvesting residues. Among those are the moisture content, which severely affects the calorific value and transportation efficiency of the residues (Murphy et al. 2012; Röser et al. 2011), and ash and inorganic (also called nutrient) contents that impact the biomass fuel quality (Gautam et al. 2012; Brand et al. 2011) and thus the chemistry/emission of the combustion process and, accordingly, the profitability of the energy plant. Biomass materials come with noticeable amounts of minerals, e.g., potassium, sodium, calcium, and magnesium, which, if combusted, interact with other elements and cause fouling, slagging, and corrosion in burners/boilers (Raask 1985). Greene et al. (2014) studied various methods for reducing moisture and ash content in logging residues and estimated the delivered cost to be a function of two factors: (i) moisture and (ii) ash content. They reported a 50% decrease in delivered cost (on an energy basis – \$/GJ) with a decrease in moisture content from 55 to 30%. Bennamoun et al. (2017) simulated the effect of varying the moisture content of forest harvest residues on a supply chain strategy in the province of New Brunswick, Canada. They mainly looked into the effect of weather conditions on residue moisture content. Miller et al. (2007) studied the effect of the inorganic composition of grass, manure, and wood biofuels on ash behaviour in combustion systems. They observed a decrease in the ash melting point with an increase in the amount of alkali metals (e.g., potassium and sodium) and alkali earth metals (e.g., calcium and magnesium), which commonly results in clinkering, ash deposition, and/or slagging in the boiler. Miles et al. (1996) analyzed minerals in biomass and their impact on the combustion of biomass. They found forest harvesting residues to have 0.34 kg/GJ volatile alkali, which melts during the combustion process or vaporizes and condenses on boiler tubes.

Forest harvest residues, when collected, might be stored on-site for a while or immediately removed from the forest. Nevertheless, there is very limited information available in the public domain on the variation of the key properties of forest harvest residue, i.e., moisture, ash, and inorganic contents, over time from immediately after collecting until it is taken from the forest. This is critical since these parameters change with time, and there should be an optimum time when they are at their lowest. Also, structuring the pile, in terms of size of the residue, as well as the height and geographical orientation of the pile, impact the variation of moisture, ash, and inorganic contents throughout the year. To the authors' best knowledge, no one has previously investigated this topic either. Delivering the residue from the forest when the key properties are at their minimum would increase transportation, as well as combustion process efficiency, and lower maintenance costs of forest residue-burning apparatuses.

This research investigated the effect of time of the year on the variation of moisture, ash, and inorganic contents of forest harvesting residues in the boreal forests of Alberta, Canada. Samples were made of two types of forest harvesting residues (pine and aspen) from various parts of the tree (leaves and foliage, branchlet, branch and stem), both inside and outside, and from all four geographical directions of the sample piles. The results were correlated to the most important of the drying process governing factors, that is, air temperature, relative humidity,

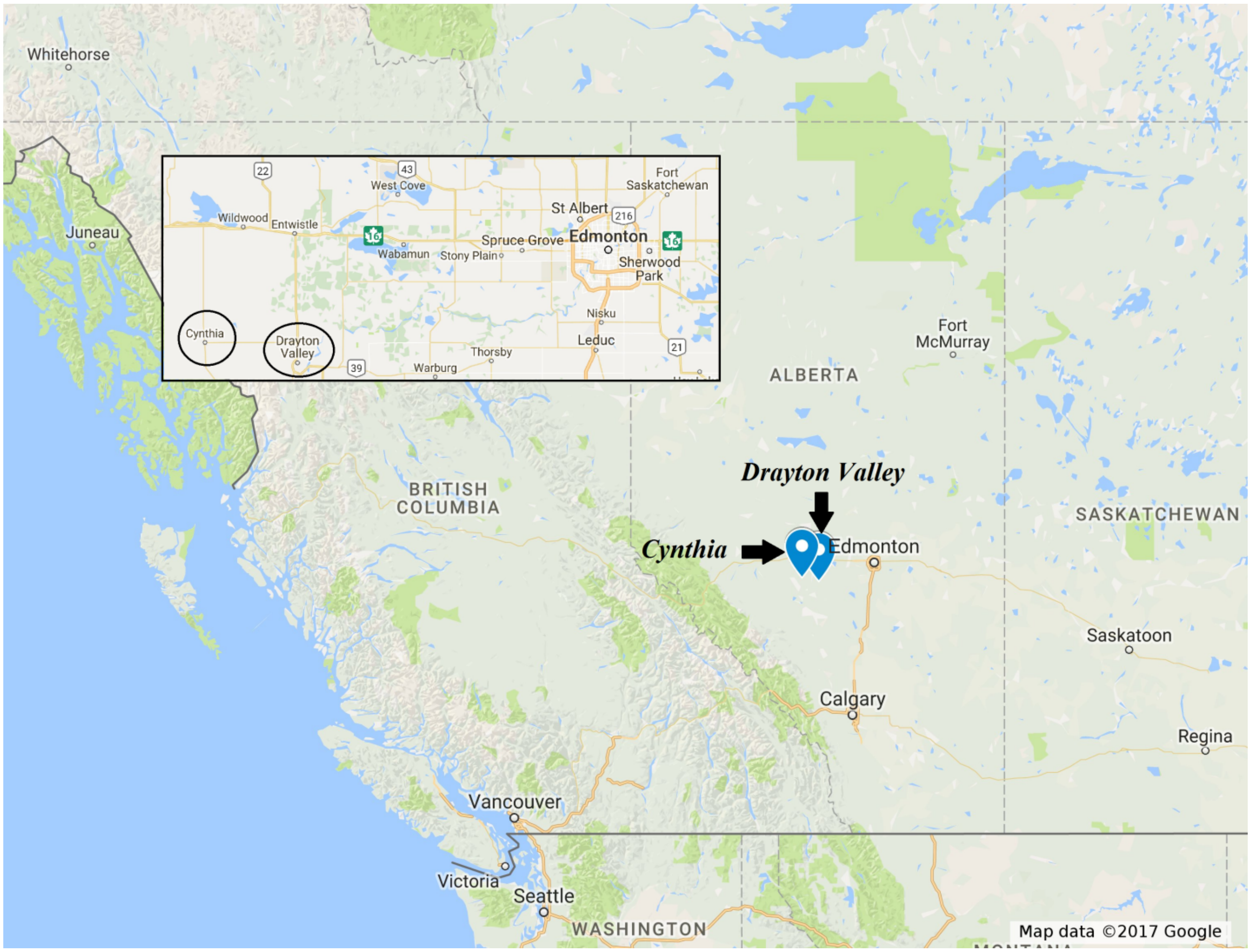

Fig. 1. Geographical locations of the two sites at Cynthia and Drayton Valley in the Province of Alberta, Canada, where forest harvesting residue samples were collected (Google, n.d.).

precipitation, and wind direction throughout the study. At the end of this paper, recommendations are made not only on the appropriate time to remove the residues from the forest but on how to size and orient the residue bales on-site to minimize the content of the key parameters over time. Also, estimates are made on how much the variation in key parameters helps, economically and technically, improve transportation and combustion. The results will be well applicable to the northern Nearctic as well as northwest and northeast Palearctic realms that share similar climate patterns. The findings will help the forestry sector to efficiently manage the harvest residues not only to address the environmental concerns associated with current practices but also to establish a secondary source of revenue and help improve the bioenergy economy.

METHODS AND DATA

Experimental procedure

The experiments were conducted over two successive years. During the first year (2011), pine tree (scientific name: *Pinus*) residues were collected in two piles (each one about 3m long, 3m wide and 2m tall) in April and stored in Drayton Valley (53.2215° N, 114.9767° W), Alberta, Canada. In the second year (2012), aspen tree (scientific name: *Populus tremuloides*) residues were collected at the same time, i.e., April, in two piles and stored in Cynthia, Alberta, Canada (see Fig. 1). Samples were collected from all parts of the tree residue, including leaves and foliage, branchlets, branches, and stems, which were categorized into three size groups based on their cross-section area: small (leaves and foliage), medium (branchlet), and large (branch and stem) (Fig. 2a). Samples were taken from four geographical directions, as well as from inside and outside the pile (for a total of 48 samples every two weeks). Temperature and relative humidity sensors (HOBO U23 Pro v2, Onset Instrument, Bourne, MA) mounted inside, and outside the pile. A precipitation sensor (HOBO Data-Logging Rain Gauge - RG3, Onset Instrument, Bourne, MA) was used to record local weather conditions during the study period (Figs. 2b, 2c, and 2d). Samples were collected every 15 days between April and October 2011 and 2012, and the average time between collecting, preparing, and analyzing samples was 10 days. When received in the

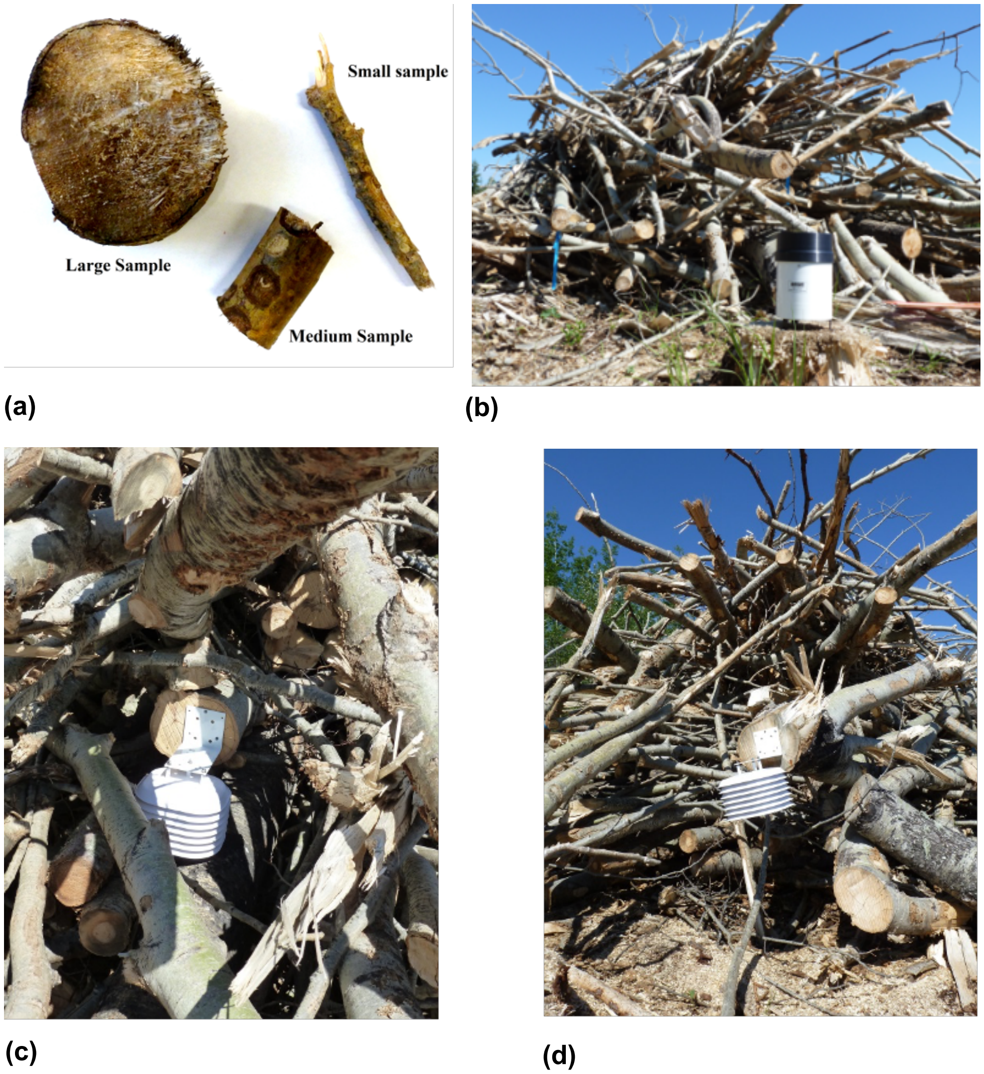

Fig. 2. (a) Small, medium, and large samples of forest harvesting residues, (b) A pile of forest harvesting residue with precipitation sensor, (c) Temperature and relative humidity sensor mounted inside the pile, (d) Temperature and relative humidity sensor mounted outside the pile.

laboratory, samples were cut into smaller pieces and their moisture content measured according to the ASABE S358.2 standard (ASABE, 2008), inorganic contents were analyzed using a spectrometer (iCAP 6000, Thermo Scientific, Waltham, MA, USA), and ash content was measured following the National Renewable Energy Laboratory (NREL) technical procedure TP-510-42622 (Sluiter et al. 2005). Ash and inorganics were measured only for the samples made within the second year of the study, i.e., 2012. The data from sensors were analyzed once at the end of each study period in October. More than one sensor was mounted on site since local wildlife, mostly bears, are used to take sensors away.

Statistical analysis

Moisture, ash and inorganic contents of forest harvesting residues were analyzed using factorial ANOVA model in R software (version 3.5.0). Time of the sampling throughout the study period, size of the sample, sampling from inside/outside of the pile, and sampling at various geographical directions of the pile were all considered fixed effects. When significant differences were evidenced, pairwise comparisons were made via Tukey's Honest Significant Difference (HSD) procedure at the significance level of 0.05 (95% confidence interval). While a four-way factorial ANOVA model was used to analyze the moisture content, a three-way factorial ANOVA model was applied to ash, Calcium, Potassium and Magnesium data, following a log transformation to satisfy the normality assumption. Likelihood Ratio (LR) tests were conducted in ANOVA to test the null hypothesis of no effects. The test statistics followed F distributions. If the test statistic is greater or equal than the critical value on the corresponding F distribution, the null hypothesis will be rejected.

RESULTS AND DISCUSSION

In this section, the variation of moisture content as a function of size (small, medium, large) and position (north, south, west, east, inside, or outside of the pile) of the sample throughout the study is discussed and correlated to the factors involved in drying process including air temperature, relative humidity, precipitation, and wind direction throughout the study. Also, the change in the ash and inorganic contents of the samples is similarly reviewed. The results in sections 3.1 and 3.2 are all presented for aspen samples made in 2012 in Cynthia, Alberta, Canada. Section 3.3 compares the aspen results with those of pine made in 2011. Section 3.4 investigates the impacts of moisture and inorganic contents on the technical and economic features of the biomass supply chain and biomass conversion facility.

Moisture content

Figure 3 presents the variation of moisture content for three sample sizes throughout the study. The effect of months of the year ($P < 2e\text{-}16$), size of the sample ($P < 2e\text{-}16$), and their interaction ($P = 0.0002$) were found statistically significant (Table 1). The general trend is a decrease from April to September, followed by a slight increase in October. This is in agreement with the results by Routa et al. (2015), who reported the moisture content of forestry products (i.e., logs, residue, etc.) in the boreal and temperate conditions of the northern hemisphere to drop rapidly during spring and summer and to rise in late summer and early fall due to the decreased evaporation rate. The results presented here for every single point in time is the average value for the results from inside and outside as well as from the south, north, east, and west parts of the pile for a given sample size. Large, medium, and small samples came with changes in moisture content throughout the study from 38% to 23%, 35% to 19%, and 25% to 20%, respectively. A 50% reduction in the moisture content of large-size samples by the end of September, i.e. from 38% to 19%, would bring about a noticeable increase in forest harvesting residue bulk density and, accordingly, transportation efficiency and sustainability of the entire supply chain. As shown in Fig. 3, the larger the size of the particle, the higher the average moisture content is, since the larger sample contains more moisture in a green state and retains it longer. Large-sized samples contain a greater amount of xylem, the water transport tissue of the plant; they also have a large ratio of volume-to-surface area, which in turn slows down the drying process.

Figure 4 shows the change in local temperature and relative humidity and the monthly precipitations at the experiment site in Cynthia, Alberta. Two sets of data are reported here: the data recorded on the site and the data reported by Alberta Climate Information Services (ACIS) for the nearest weather station in Violet Grove, 40 km southeast of Cynthia and 10 km southwest of Drayton Valley (Current and Historical Alberta Weather Station Data Viewer 2017). As observed in Fig. 4, relative humidity and temperature follow opposite trends. While an increase

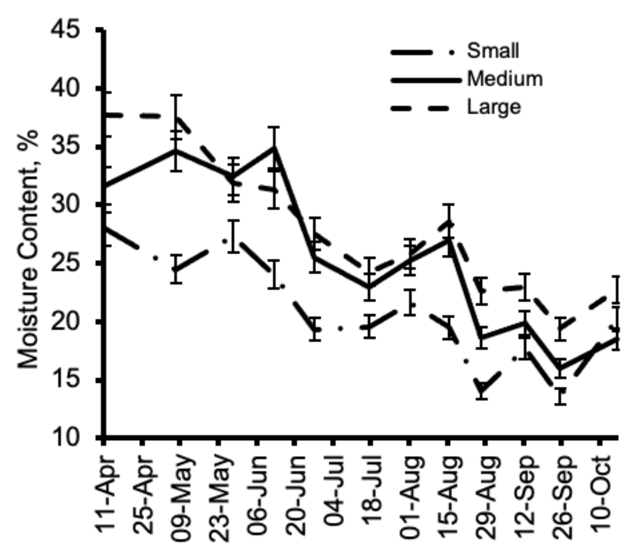

Fig. 3. Variation of moisture content versus time for three aspen sample sizes in 2012.

in relative humidity slows down the evaporation of moisture to the air, it also increases the equilibrium point for biomass. This can cause even an increase in the final moisture content, adding to the time required to dry the residues. Periods of higher temperatures (above 15°C) lower moisture content through the evaporation of forest residues stored on-site (Bennamoun et al. 2017; Bennamoun and Belhamri 2008). Comparing Figs. 3 and 4a, it can be observed that the moisture content follows a similar trend as relative humidity with maximums in June and August, followed by a decrease in September, after which it increases again. Also, an increase in temperature from 13°C in early June to 24°C in mid-July reduced moisture content by 10% in the period of the study. High precipitation has been shown to increase moisture content (Bennamoun et al. 2017; Nilsson et al. 2013). However, due to variations in temperature and relative humidity, it was not convenient to track the effect of each parameter individually.

The effect of sampling from inside or outside of the pile ($P = 0.0064$), also from various geographical_orientations ($P = 3.5e\text{-}08$) were found significant as well (Table 1). Figure 5(a) shows the variation in moisture content in the samples made from inside and outside of the aspen pile. The inside samples had an average moisture content of 2% greater than the samples from outside the pile, attributable to less exposure to sunlight. Figure 5(b) shows the change in moisture content as a function of the geographical direction of the pile from which the samples were taken. Samples taken from the west side of the pile had, on average, higher moisture content (24.6%) than those from the north (23.8%), east (22.8%), and south (20.7%). Based on Fig. 5(b), it can be observed that mid-May until mid-July, the prevailing weather approaches mostly from the east, and so the east side of the pile receives the greatest amount of moisture in wind/weather events. However, from mid-July until October, the wind blows predominantly from

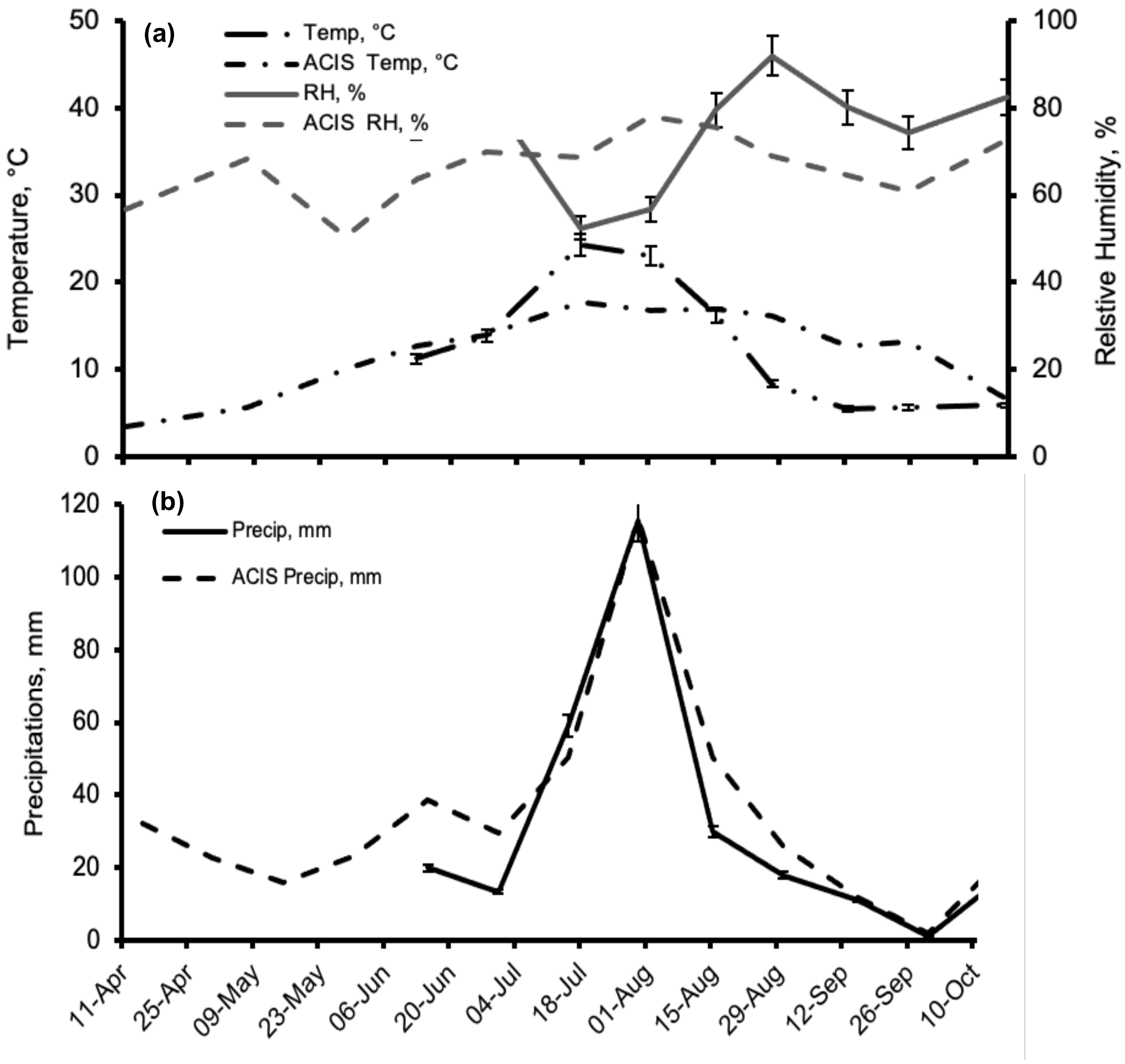

Fig. 4. (a) Variation of local temperature and relative humidity within the period of study in Cynthia, Alberta in 2012, (b) Measured vs. reported (ACIS) accumulated monthly precipitations within the period of study in Cynthia, Alberta in 2012.

Table 1. Analysis of variance for moisture content as a function of time of the year, size of the sample, sampling from inside and outside of the pile, and sampling at various geographical direction of the pile.

Effect	df	F Value	P-Value
T[1]	10	31.79	<2e-16
S[2]	2	83.78	<2e-16
I/O[3]	1	7.55	0.0064
N/S/W/E[4]	3	13.43	3.5e-08
T × S	20	2.71	0.0002

[1] Time of the year
[2] Size of the sample
[3] Sampling from inside/outside of the pile
[4] Sampling from the various geographical orientation of the pile

the west and, therefore, the west side of the pile has higher moisture. The south side of the pile contains the least amount of moisture throughout the study.

While the effect of the month of the year was found significant in ANOVA, there is a great interest in finding the optimal time of the year to take the forest harvesting residues from the forest. Based on Fig. 3, the month of September appears to be the best time for this. This was statistically confirmed, when Tukey's HSD procedure provided pairwise comparisons between September 25 and the rest of the sampling dates, as per Fig. 6. It is observed that the majority of confidence intervals do not contain zero, i.e., September 25 is significant in terms of moisture content. Therefore, late September can be generally recommended as the year's optimum time to remove the forest harvesting residues from the forest. In September, the

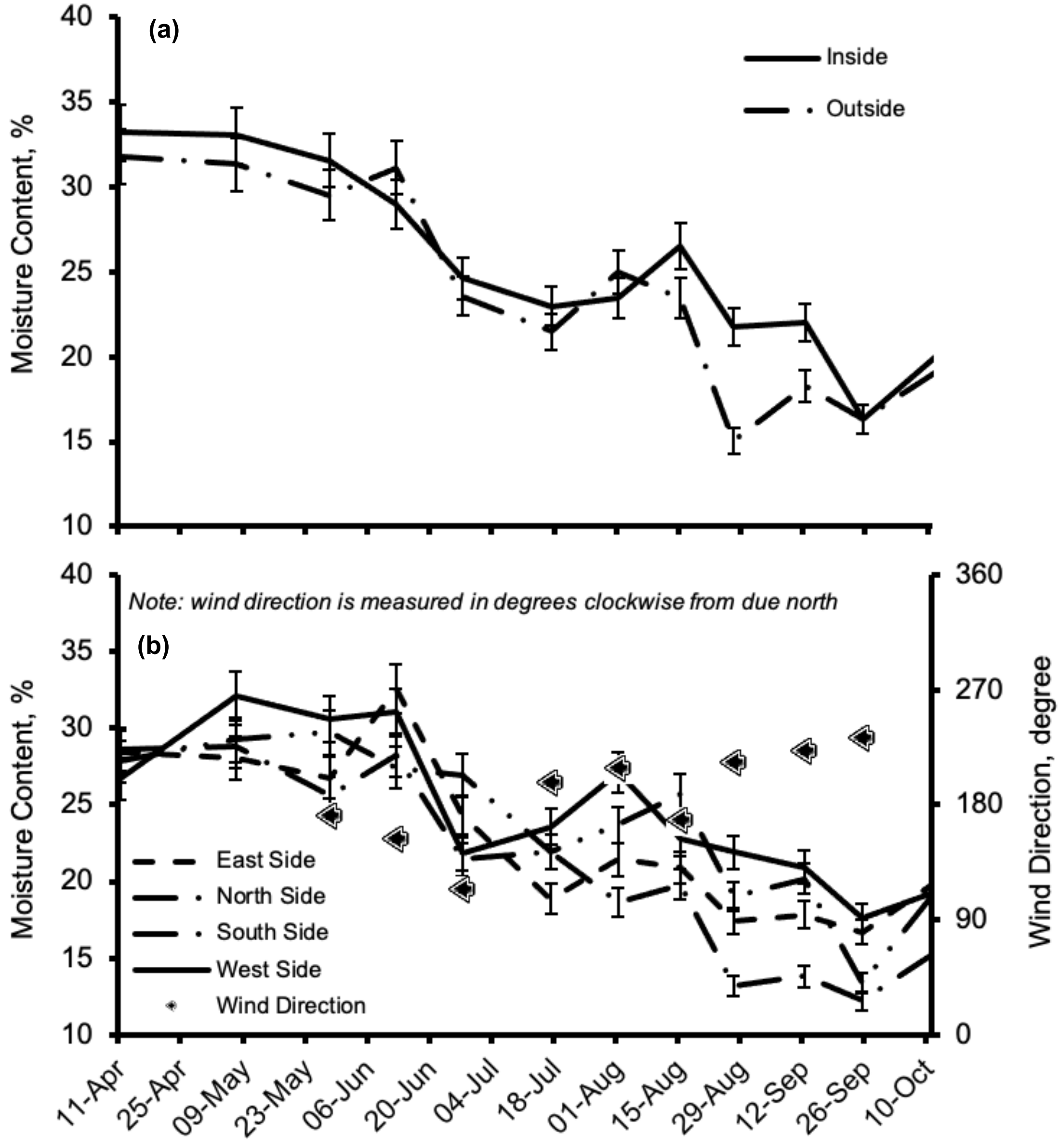

Fig. 5. (a) Variation in moisture content over time for aspen samples taken from inside and outside the pile in 2013, (b) Variation in moisture content over time for aspen samples taken from the pile's four geographical directions in 2013, together with variation in wind direction (measured 10 m above the ground – reported by ACIS) during the period of study, Violet Grove station, Alberta.

residues come with an average of 42% less moisture content than residues sampled at the beginning of the study period, i.e., April.

One can now conclude that making tall piles (to get less accumulation of residues inside and more exposure to sunlight) of mainly small-size forest harvesting residues and orienting the pile southward will reduce the absorption of moisture by residues. However, variations in ash and inorganics need to be taken into account before making a general recommendation about the size of the residues and the height and orientation of the piles.

Ash and inorganic contents

Using a three-way factorial ANOVA model, the null hypotheses of no sample size effect (P < 2e-16) and no inside/outside effect (P = 0.0166) on samples ash contents were rejected at P < 0.05, i.e., the effects of the size of the sample as well as sampling from inside/outside of the pile on samples ash contents are both statistically significant. However, the effect of time of sampling throughout the study period was not found significant (P = 0.074) at a 95% level of confidence, but it was found significant at a 90% level (Table 2).

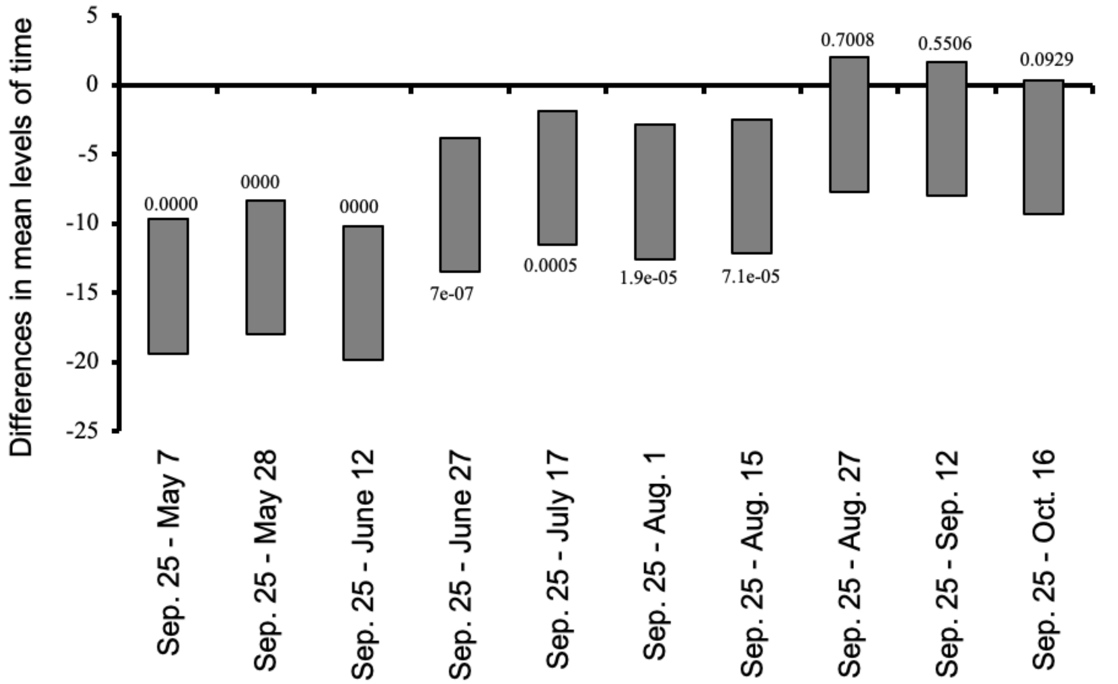

Fig. 6. Tukey's HSD procedure for the effect of sampling date on the sample's moisture content. Labels represent the *P* adjusted values; the *P* values after adjustment for the multiple comparisons.

Figure 7(a) shows the variation in ash content in aspen samples during this study. The average ash content for small size samples is higher than that for medium and large-size samples. This is because of the high concentration of ash in the tree's bark tissues (Bowyer et al. 2003) and because smaller samples (foliage, branchlets) have a much higher proportion of bark than larger branches and stems (Hakkila 1989). Considering sampling from inside or outside of the pile, Fig. 8 shows the residues sampled from inside of the pile have ash contents, on average, 1.65% higher than those sampled from outside because of smaller leaching due to less exposure to precipitations.

Figure 7(b-d) shows the variation in calcium (Ca), potassium (K), and magnesium (Mg) over time. Using a three-way ANOVA model for calcium content, only the effect of the size of the sample was found statistically significant with a P-value of $< 2e\text{-}16$ vs. P-value of 0.963 for the effect of the time and 0.548 for the effect of sampling from inside or outside of the pile (Table 2). Calcium concentration in residues in small samples increased rapidly during the first few months. Since calcium is a structural component of vegetal tissues whose release depends on microbial activity rather than leaching (Blair 1988), its concentration increases as decomposition proceeds. It is released only at advanced stages of decomposition (Ouro et

Table 2. Analysis of variance for ash, calcium, potassium, and magnesium contents as a function of time of the year, size of the sample, sampling from inside and outside of the pile and their interactions.

Inorganics / Factor	Ash			Calcium			Potassium			Magnesium		
	dF	F Value	P-Value	dF	F Value	P-Value	dF	F Value	P-Value	dF	F Value	P-Value
T[1]	11	1.78	0.074	11	0.37	0.963	11	3.81	**0.0002**	11	0.70	0.7379
S[2]	2	388.34	**0.0000**	2	168.96	**0.000**	2	132.02	**0.0000**	2	41.50	**0.0000**
I/O[3]	1	6.02	**0.0166**	1	0.36	0.548	1	1.95	0.1666	1	0.88	0.3507
T × S	22	1.56	0.0835	22	7.61	**0.000**	22	8.90	**0.0000**	22	2.75	**0.0007**
T × I/O	11	0.46	0.9202	11	0.68	0.751	11	0.77	0.6644	11	1.43	0.1796
S × I/O	2	1.19	0.3107	2	0.80	0.455	2	0.94	0.3955	2	1.10	0.3375
T × S × I/O	22	0.74	0.7838	22	0.84	0.666	22	0.74	0.7867	22	0.96	0.5254

[1] Time of the year
[2] Size of the sample
[3] Sampling from inside/outside of the pile

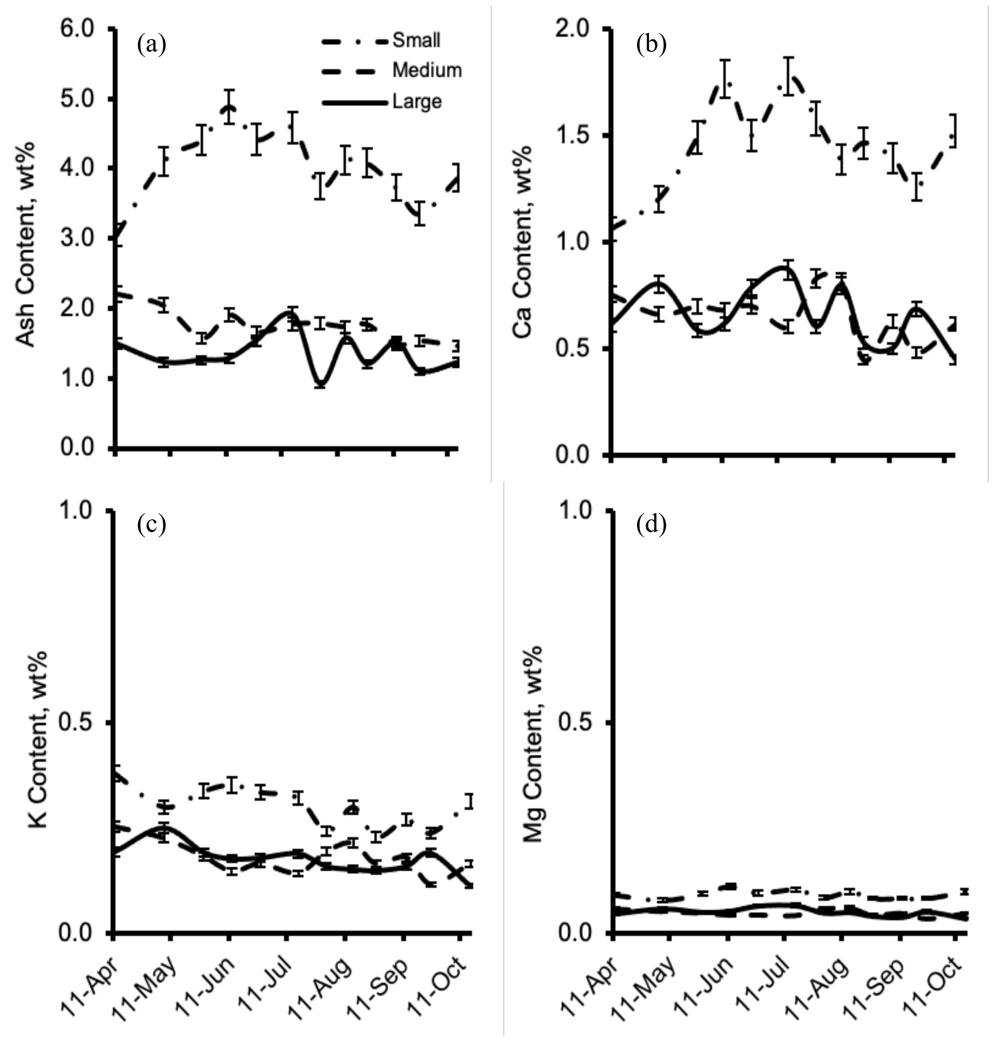

Fig. 7. Variation of (a) ash, (b) calcium, (c) potassium, and (d) magnesium over time for three different sample sizes of aspen.

al. 2001). Since decomposition proceeds slower in medium and large samples, 92% and 55% of the initial calcium content was present in medium and large samples, respectively, at the end of the study. Finally, while both the effects of time of sampling (P = 0.0002) and the size of samples (P < 2e-16) were found statistically significant for Potassium, only the size of the sample was found significant in the case of Magnesium (P = 1.03e-12) (Table 2). Potassium release from residues was initially relatively rapid for small and medium samples. This is attributed mostly to the leaching of highly water-soluble components (and not decomposition), as similarly observed by Sanchez et al. (2010) and Girisha et al. (2003). Magnesium loss, on the other hand, occurred at a relatively constant rate and the change in magnesium concentration was negligible throughout the study. As can be observed (Fig. 8), no meaningful difference was found between the inorganic contents of the residues sampled from inside and outside of the pile.

Regarding the optimum time of the year, in terms of ash and inorganic contents, to take the forest harvesting residues from the forest, Tukey's HSD procedure failed to detect any statistically significant difference between sampling dates throughout the study; thus, no recommendation can be made. However, one can see a benefit in making tall (see the variation of ash content in Fig. 8) piles from medium and large-size residues (see the variation of ash, calcium, and potassium in Fig. 7) to retain the least content of ash and inorganics throughout the year. This contrasts with the conclusion made previously in section 3.1, considering variations in moisture content only of tall piles of mainly small-size residues. Since there is ~6% difference in the moisture content of small and large samples vs. ~2.0% in ash and ~0.6% in calcium content on the recommended date of September 25, a compromise should be made in favour of low moisture content instead of low ash and inorganics to retain. In conclusion, tall piles of small-size forest residues, oriented southward, and stored on-site in late September are recommended.

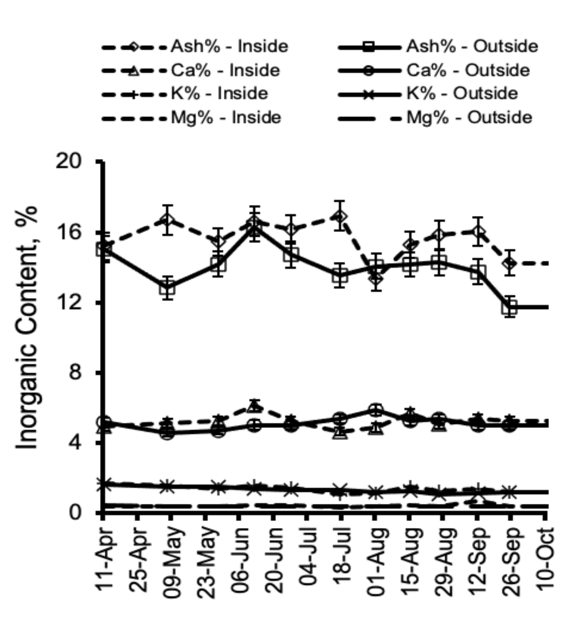

Fig. 8. Variation of ash, calcium, potassium, and magnesium over time for aspen samples (average of all three sizes) taken from inside and outside the pile in 2013.

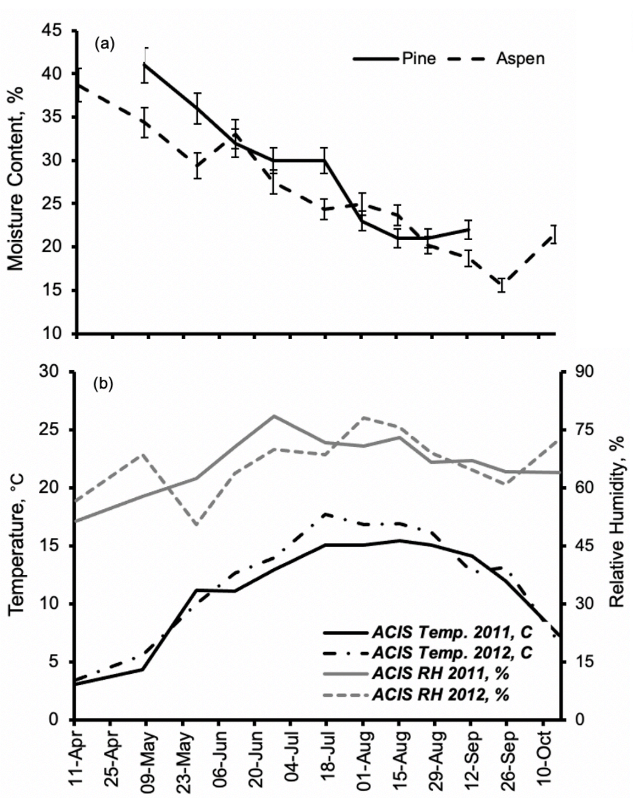

Fig. 9. (a) Variations in moisture content over time for large-size samples of aspen and pine, (b) Measured vs. reported (ACIS) local temperature and relative humidity during the period of study, taken from Violet Grove in 2011 and 2012.

Sample type (aspen vs. pine)

When comparing aspen samples (made in 2012 in Cynthia, AB) with pine's (made in 2011 in Drayton Valley, AB), it was observed (Fig. 9a) that pine came with higher average moisture content than aspen. This is attributed to the weather conditions in 2011, lower temperatures and higher relative humidity, that resulted in less evaporation and, thus, higher moisture. The ash and inorganic contents were measured only for the aspen samples collected in 2012.

Techno-economic impacts of moisture, ash, and inorganic contents

Greene at al. (2014) reported the delivered cost ($/GJ) of forest harvesting residues as a function of the moisture content. The authors calculated the delivered cost of logging residues from a Roundwood harvest or a chain-flail delimber to be 0.064 $/GJ/%MC. Considering a reduction in large-size aspen forest harvesting residue samples with moisture content from 37.52 to 19.38%, 1.16$/GJ in delivery costs can be saved if the residue is taken out from the forest in September. Belart et al. (2017) calculated (Eq. 1) the amount of wood (ODMT) required to produce one MWh energy based on wood moisture content. According to Belart et al. (2017), the 51.6% reduction (from 37.52 to 19.38%) in the moisture content of large-size aspen forest harvesting residues from April to September results in a 9.7% reduction in the amount of forest harvesting residue required to produce 1 MWh electricity.

$$ODMT \ / \ MWh = 0.0001 \ 〖MC〗^2 - 0.0014MC + 0.7291 \qquad (1)$$

where *ODMT*/*MWh* is oven-dried metric tonnes of residue per *MWh,* and *MC* is the moisture content (% wet basis) of the residue.

Forbes et al. (2014) investigated 7 different biomass fuel types for their physical, chemical, thermo-gravimetric, and combustion properties. They observed that the ash and clinker recovered from the boiler grate decreased up to three folds for low inorganic content residues of pine, spruce, brash, and willow, compared to those with higher contents such as miscanthus.

CONCLUSIONS

This research aimed to investigate the variation of moisture, ash and inorganic contents of pine and aspen forest harvesting residues from April till October in two successive years. Mainly, the effect of the size of the residues, as well as the structure and orientation of the piles of the residues were studied. It was also investigated the best time of the year to truck the residues out of the forest in terms of moisture, ash and inorganic contents at their minimum. With respect to all the considerations, recommendations were made to prepare tall piles of small-size forest residues, orienting the piles southward, and storing the piles onsite to remove from the forest in late September.

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