

Heterogeneity of Forest Harvest Residue from Eastern Ontario Biomass Harvests

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Abstract

The environmental and economic problems associated with the use of fossil-based fuels have encouraged a shift to abundant renewable resources, such as forest residues. However, before forest residues can be used as an industrial resource, their properties must be known. This study determined the physical (moisture content, bulk density, and wood/bark ratio) and thermal (elemental composition, thermal reactivity, and energy value) properties of heterogeneous residues generated during commercial harvesting on two forest sites within the Great Lakes St. Lawrence forest of southeastern Ontario. Other factors that can affect these properties, such as duration of storage and location in a storage pile, were also evaluated. A physical fractionation treatment was also investigated as a means of value addition to forest residues. Long-term storage in an uncovered pile resulted in the forest biomass on the surface losing moisture (19.3%) and the biomass on the inside gaining moisture (73.1%). In addition, storage caused an increase in bulk density and a reduction in chloride content. The higher heating value of the forest harvest residues averaged 19.0 MJ/kg (standard deviation [SD] = 0.3 MJ/kg), with an average energy density of 1,991 MJ/m³ (SD = 628 MJ/m³). This study also found that size fractionation resulted in fractions with more uniform properties.

Concerns about climate change, increasing fossil fuel prices, and uncertainty over future energy supplies are major drivers in the necessary shift to a low-carbon economy through the use of renewable resources, including residual forest biomass (Ontario Ministry of Natural Resources [OMNR] 2008). Canada is richly endowed with forest resources with approximately 1 million hectares of commercial forests harvested annually, producing 193 million m³ of wood (Ralevic et al. 2008, Standing Committee of Natural Resources 2008, Natural Resources Canada–Canadian Forest Service 2009). Concerns in the Canadian forest sector, including more complete utilization of forest resources, markets for lower-end fiber quality material, improving forest management, and interest by nontraditional forest sector enterprises in using forest resources, have created the opportunity for dramatic transformation of the sector.

Residual forest biomass may be generated either (1) during the harvesting and extraction of merchantable trees from forest sites (referred to in this article as forest residues) or (2) during processing of logs at primary or secondary manufacturing facilities (referred to in this article as mill residue). In this article, the term “forest residues” more specifically refers to low-value material that results from commercial thinnings and/or harvesting of merchantable tree species (tops and limbs); rejected materials that do not

meet mill specifications, such as logs that are undersized and/or that have cankers or other defects; tree species that are currently not marketable as traditional forest products; and trees salvaged after being damaged by fire, wind, and other types of forest disturbances (Ralevic et al. 2008).

The amount of forest residues generated during forest harvest operations are highly variable and depend on forest type, harvesting method, and site characteristics. Broad nationwide estimates for forest residues in Canada range from 8.6 to 59.5 million dry tonnes per yr (Parzei et al. 2014). Traditionally in Canada, these residues are either left

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Forest Prod. J. 66(3/4):164–175.

doi:10.13073/FPJ-D-14-00098

on the forest floor as an aid for biodiversity and nutrient cycling or piled at roadsides to be burned for no economic consideration (Mitchell 2005, OMNR 2008). This vast resource has a vital role to play in Canada's shift to a low-carbon bioeconomy when used as an alternative to fossil fuels in direct combustion for heat or in the generation of power.

There is opportunity in Ontario for utilization of its substantial amount of forest residues, industrial capacity, infrastructure, and expertise to support sustainable growth and create prosperity in northern and rural economies (OMNR 2008). In support of this objective, operational biomass harvests of (1) shelterwood and (2) modified clear-cut were carried out on two forest sites in the Great Lakes St. Lawrence (GLSL) region of eastern Ontario to evaluate technical feasibility, operational parameters, and cost for the recovery of forest residues (Cormier and Tremblay 2009).

To determine the suitability of forest residues as a feedstock for specific applications, its properties and characteristics must be well understood. Characterization data to date are largely species and component specific and based on recently harvested material. However, residues that are and that will be available from forest harvest operations are complex in terms of species and tree component composition, and this complexity is further complicated by other factors, including season of harvest, on-site handling, and storage. If forest residues are to gain acceptance for new applications, it is vital that the characteristics of the whole rather than the parts are understood.

Thus, in this study, we determined the physical characteristics (moisture content [MC], bulk density, and wood/bark ratio) and thermochemical characteristics (elemental composition, thermal reactivity, and energy value) of forest residues generated from two operational biomass harvest trial sites in eastern Ontario. These characteristics affect overall processing, transportation, and storage and are meaningful in determining the potential of the materials as feedstock for bioenergy and biochemical applications.

Materials and Methods

Materials

Sample materials were obtained from operational biomass trial sites in the GLSL region in eastern Ontario.

Site 1.—Site 1 was a private woodlot 24 km southwest of Eganville, Ontario (45°45'N, 77°27'W). This site included a total of 23.7 hectares (Block 1). Biomass was from the tops and limbs of merchantable trembling aspen (*Populus tremuloides* Michx.), >20 cm diameter at breast height (DBH), and whole trees of unmerchantable trembling aspen, sugar maple (*Acer saccharum* Marsh.), and basswood (*Tilia americana* L.). Trembling aspen made up 80 percent of the merchantable volume, with sugar maple and basswood accounting for the remaining 20 percent. A full-tree harvesting system was used, employing a feller buncher and a grapple skidder. The topping was done at roadside, and slashed logs were separated into sawlogs and pulpwood with biomass making the third pile (Fig. 1). Harvesting and comminution were done in late spring with a Rotochopper MC 266 grinder using a screen size of 3.5 inches. The grinding of the biomass was done shortly after harvest and was ground directly into live-floor chip vans. Biomass samples were obtained at time of grinding.

Site 2.—Site 2 was crown land in the Mazinaw Lanark Forest, 10 km south of Denbigh, Ontario (45°02'N, 77°21'W). The two harvesting treatments on this site included a modified single-tree selection cut (3.4 ha; partial cut, Block 2) and a modified clear-cut (14.3 ha; Block 3). Block 2 was composed of sugar maple, with a minor component of red oak (*Quercus rubra*), red maple (*Acer rubrum* L.), white pine (*Pinus strobus*), and trembling aspen. Block 3 was composed of intolerant hardwoods, such as trembling aspen (45%), red maple (18%), and white birch (17%; *Betula papyrifera* Marsh.). Small-diameter, noncommercial trees of balsam fir (*Abies balsamea* L. (Mill)), white cedar (*Thuja occidentalis* L.), trembling aspen, white birch, and red maple were also present. Both blocks on this site were harvested in July through early August. Comminution was done in September following the harvest.

In Block 2, a single-tree selection cut was used. The larger branches were shaved at the stump in order to minimize damage to residual standing trees. All tops and limbs were included in the biomass sample for this block. In Block 3, a semimechanized full-tree system was used. The feller buncher cut all commercially valuable species with DBH greater than 10 cm. Trees were sorted into two piles: one for conventional commercial trees and the other for the small trees and noncommercial species (later to be ground as biomass). Both piles were skidded to the roadside, where the tops and limbs from the commercial trees were manually removed and piled with the small, noncommercial pile.

A 2007 Rotochopper B66 grinder using a top screen size of 6 inches and a bottom screen size of 4 inches was used for comminution. The biomass was piled directly on the ground post comminution and left on the landing (Fig. 2). Some of the material could not be ground because of heavy rock contamination caused by the piling technique.

Three forest residues were sampled from the three harvest blocks (i.e., one per block) for laboratory analysis immediately following comminution. After a year of storage on-site, two additional samples were obtained from the surface and 60 cm inside the piles at Block 3. This sampling was repeated after the second year of storage. Forest residues were placed into airtight bags and stored at -3°C until time of testing. A complete description of the seven forest residue samples used in this study is given in Table 1. A selection of forest residue samples is illustrated in Figure 3.

Table 1.—Descriptive summary of forest residues.^a

| Sample | Harvest block | Harvest type | Time of collection | Position in pile |
|--------------|---------------|--------------|--------------------|------------------|
| HB1-CC-T0-P0 | HB1 | CC | T0 | P0 |
| HB2-PC-T0-P0 | HB2 | PC | T0 | P0 |
| HB3-CC-T0-P0 | HB3 | CC | T0 | P0 |
| HB3-CC-T1-P1 | HB3 | CC | T1 | P1 |
| HB3-CC-T1-P2 | HB3 | CC | T1 | P2 |
| HB3-CC-T2-P1 | HB3 | CC | T2 | P1 |
| HB3-CC-T2-P2 | HB3 | CC | T2 | P2 |

^a Harvest block: HB1 = Eganville, Ontario; HB2 = Denbigh, Ontario; HB3 = Denbigh, Ontario. Harvest type: CC = clear-cut; PC = partial cut. Time of collection: T0 = after comminution; T1 = 1 year of storage; T2 = 2 years of storage. Position on pile: P0 = representative sampling; P1 = from surface of pile; P2 = from 60 cm inside of pile.



Figure 1.—Harvest separated into sawlogs, pulpwood, and forest residue piles (Cormier and Tremblay 2009).

Methods

Physical characterization.—The “as-received” MC of forest residue samples was determined by drying approximately 20 g of test sample in an oven preset to $105^{\circ}\text{C} \pm 3^{\circ}\text{C}$ for 16 hours following ASTM E 871-82 (ASTM International 2006a). The MC was also determined each time the

mass of a test sample was taken for a specific experiment in order to report results on an oven-dry basis.

The bulk densities of as-received forest residue samples were determined following CEN/TS 15103 (European Committee for Standardization [CEN] 2005). Pieces extending above the top of the cylinder were sheared off



Figure 2.—Piles of comminuted forest residues (Acquah 2010).



Figure 3.—Forest residues samples: (a) HB1-CC-T0-P0, (b) HB2-PC-T0-P0, (c) HB3-CC-T1-P1, and (d) HB3-CC-T1-P2.

instead of pulled out (as per CEN/TS 15103). Three replicates of each sample were performed for each test and the average and standard deviation reported.

The bulk density was calculated based on both its as-received mass (wet bulk density) and its oven-dry mass (dry bulk density). The wood/bark ratio was calculated on an oven-dry mass basis. The bark was manually separated from the wood material and scraped off with the aid of a knife when necessary. Small material that could not be distinguished as bark or wood was labeled as fines.

Fractionation by size was accomplished with a vibrating screen equipped with two screens (Fig. 4). The upper screen had circular openings that were 31.5 mm in diameter, and the bottom screen had openings that were 12.5 mm in diameter. Materials that were retained on the top and bottom screens were designated as “large” and “medium,” respectively. Material that passed through the bottom screen was designated as “small.”

Thermochemical characterization.—The major elements in the samples (ultimate analysis) were determined using a PerkinElmer Model 2400 II CHN analyzer at a 0.3 percent detection limit. Samples were prepared by air-drying (22°C; relative humidity [RH] 30%; 72 h) and milling to pass an 80-mesh screen. The test samples were completely combusted, and the amount of carbon and hydrogen present in the carbon dioxide and water generated was calibrated against standard thermal acetanilide (C: 71.09; H: 6.71; N: 10.36) before and after samples were run. Oxygen was computed as 100 – mass of all other elements present. The

masses of elements were expressed as percentages of the moisture-free mass of test samples.

The amounts of chlorides in the forest residue samples were determined with a Dionex high-performance liquid chromatography (DX 600) system with suppressed conductivity operated with an ASRS ultra II (4 mm) suppressor following CEN/TS 15289 (CEN 2006), ISO 10304-1 (International Organization for Standardization [ISO] 2007), and Dionex Application Note 113 (Dionex Corporation 1999). The eluent used was 15 mM NaOH with a set flow rate of 1.0 mL/min and injection volume of 10 μ L. An IonPac AS11 HC (4 by 250-mm) column was used to resolve anions found in sample solutions. The chloride peak had a retention time of 3.27 minutes based on standard sodium chloride. The total run time for analysis of a test sample was 10 minutes. Test samples were calibrated against standard 10-, 5-, 2.5-, and 0-ppm sodium chloride solutions. Sample solutions were collected following the complete combustion of the samples in the bomb calorimeter.

Proximate analysis was performed to determine the volatile matter, fixed carbon, and ash content (i.e., thermal reactivity) of samples using a TA Q500 thermogravimetric analyzer as recommended by Klass (1998). Standard test methods that determine these components separately are believed to be inferior, as they do not give systematic and complete simultaneous proximate analysis (ASTM International 2006b, Vassilev et al. 2010).

For the proximate analysis, approximately 7 mg of air-dried (22°C; RH 30%; 48 h) milled (to pass a 40-mesh screen) test sample was heated to 105°C at 20°C/min in a



Figure 4.—Forest residue sample being separated into the various fractions (Acquah 2010).

nitrogen environment. The temperature was maintained at 105°C for 5 minutes to ensure that all water was evaporated before raising the temperature at a rate of 50°C/min to 600°C and holding for 7 minutes. Oxygen was introduced during the final stage to facilitate complete oxidation of the biomass and maintained for 10 minutes. The amounts of water, volatiles, fixed carbon, and ash were calculated for the sample. Mass loss (from the initial) up to a temperature of 105°C was attributed to water evaporation; mass loss at 600°C after holding for 7 minutes gave the volatile matter and mass of residue after complete oxidation was ash. The mass of fixed carbon was computed by subtracting the above three values from the initial mass.

A Parr 1108 oxygen combustion bomb calibrated with standardized benzoic acid pellets was used to determine the higher heating value (HHV; measured in megajoules per kilogram) of forest residue samples on a moisture-free basis as specified in Krigstin (1985), ASTM D2015 77 (American Society for Testing and Materials 1983), and the Operating Instructions for the 1180 Oxygen Combustion Bomb (Parr Instrument Company 2008). Approximately 400 mg of test sample ground to pass a 40-mesh screen were compressed (using the bottom of a glass vial) and completely combusted in 20 atm of oxygen. All contents in the bomb were washed with distilled water and carefully collected after combustion. This sample was stored at 4°C for chloride determination.

HHV is the maximum amount of energy that can potentially be recovered when fuel is completely combusted under adiabatic conditions. The HHV (ash-free basis) was calculated based on the ash-free mass of forest residue samples (corrected using the ash content determined in the proximate analysis). The lower heating value (LHV) was calculated using the following equation

$$\text{LHV (MJ/kg)} = \text{HHV} - 2.45 \times 0.09 \times \text{H} \quad (1)$$

where H is the percentage of hydrogen in the dry fuel determined in the ultimate analysis of forest residue sample (Hakkila and Parikka 2002).

The LHV takes into account the fact that some energy is lost in practice to vaporization of the water of formation. The net heating value (NHV) was calculated using the measured HHV and the initial MC of forest residue samples using the following equation (White et al. 1983)

$$\text{NHV (MJ/kg)} = \text{HHV}(1 - \text{MC}/100) - (2.8 \times \text{MC}/100) \quad (2)$$

Finally, the energy density (megajoules per cubic meter), which is the energy per unit volume of a fuel, was calculated as the product of the NHV and the wet bulk density (kilograms per cubic meter) of forest residue samples (Hakkila and Parikka 2002).

For each characteristic (except for carbon and hydrogen), a minimum of three replicates were performed, and their average was taken as the measured value. The R software for statistical computing package was used to perform 1-way or 2-way analysis of variance (ANOVA). One-way ANOVA was applied to the factor Harvest Block to determine differences among means of its three levels for each property of interest. For the factors Time and Position, a 2-way ANOVA was used to determine the differences in their treatment means as well as the interaction of these two factors. A Welch 2-sample *t* test and/or Tukey pairwise comparison test was used to identify significant differences between treatment means at a 95 percent confidence level.

Results and Discussion

Physical characteristics

Moisture content.—MC is an important parameter in the use of lignocellulosic biomass for fuel. High MC in biomass

negatively impacts its energy density and hence transportation costs as well as the NHV if used as a fuel. This in turn influences its economic viability. The MC must also be considered in the design of harvest and transportation equipment (Nordin 1994, Mckendry 2002, CEN 2005). Furthermore, moisture subjects biomass to an inherent instability that makes it prone to microbial degradation and subsequent dry matter loss (Tagore 2010).

The MC of as-received forest residue, expressed as a percentage of the mass of water over the green mass of the sample (MC on a wet basis), is presented in Table 2.

The MC of the three initial samples from Block 1 (HB1-CC-T0-P0), Block 2 (HB2-PC-T0-P0), and Block 3 (HB3-CC-T0-P0) fall within values reported in literature for similar species, that is, trembling aspen (45%; Mckendry 2002) and forest residue (30%–60%; Food and Agriculture Organization of the United Nations 1990). There is a significant difference in the MC of the material collected from Block 2 in comparison to materials from Blocks 1 and 3. This may be explained by the fact that the Block 2 biomass was composed entirely of tops and branches with no stem wood. Branches have been shown to possess higher moisture levels than stem wood; in addition, the MC of branches has as much as a 5 percent increasing trend from the bottom of the tree to the top (Dibdiakova and Vadla 2012). MC of freshly harvested trees varies based on the ratio of sapwood to heartwood and the ratio of bark to wood. Sapwood, being the water-conducting tissue in the tree, has higher MC than heartwood, and bark has been found, in most cases, to have higher MC than wood (Manwiller 1975, Dibdiakova and Vadla 2012). Because the biomass in this study is composed of either tops alone or tops and small-diameter hardwoods, the initial MC is expected to be higher than if using full stems as the biomass. Manwiller (1975) reported on the MC of newly harvested small-diameter hardwood trees from 22 species and found that the MC varied from a low of 46 percent (ovendry basis) to a high of 120 percent. For red maple, the MC of the branch bark (89.4%) was significantly higher than the stem wood (69.9%) and stem bark (74.4%).

The average MC of biomass piles have been reported to decrease on storage, especially if stored throughout the summer months (White et al. 1983, Nurmi and Hillerbrand 2007). In this study, the MC of stored forest residues varied significantly by position in the storage pile. The relatively

low MC of residue sampled from the surface of the pile after a year of storage (HB3-CC-T1-P1) decreased further when stored on-site for an additional year (HB3-CC-T2-P1; Table 2). The reverse was true for residue sampled 60 cm inside the pile with its MC being significantly higher than the original material. The 1-year-old residue (HB3-CC-T1-P2), which already had a relatively higher MC, showed a further increase in moisture after the second year of storage (HB3-CC-T2-P2), but was not statistically significant. A 2-way ANOVA showed that time alone did not significantly affect the MC of forest residue samples. However, position, as well as the interaction effect of time and position, did influence the MC of piled harvest residue samples.

The change in MC of biomass stored piles depends on local climatic conditions (precipitation and temperature), pile compaction, and chemical and biological activities that affect the internal temperature of the pile. In this study, the pile was repeatedly sampled during the summer months, and thus the surface of the pile was exposed to warm temperatures that expedited evaporative drying on the surface. The increase in the MC of HB3-CC-T1-P2 and HB3-CC-T2-P2 samples might be explained by the “wet lens” theory put forward by Buggelen (1999). In the phenomena observed, a pile of biomass expels heat through its top like a chimney, simultaneously drawing in fresh air from its sides. The fresh air moves with liberated moisture and tends to condense in a layer (called the wet lens) just below the surface of the pile.

Bulk density.—The bulk density of lignocellulosic biomass plays a major role in the feasibility of its procurement (in terms of storage, transportation, and handling) as a feedstock for various applications (Mckendry 2002). Bulk densities of the forest residue samples are presented in Table 2.

The wet bulk densities of forest residues samples ranged from a low of 106 kg/m³ for HB1-CC-T0-P0 to a high of 423.2 kg/m³ for HB3-CC-T2-P2. This wide variation is influenced largely by the amount of moisture in the samples. The variation in the samples decreased when bulk densities were expressed on ovendry mass of samples.

The dry bulk densities of forest residues from Blocks 1 and 3 were significantly lower than that sampled from Block 2, even though different grinders (and final screen size) were used on Block 1 versus Blocks 2 and 3. Hence, the characteristics of the harvest residue appear to influence the bulk density of the final ground biomass. The notably high bulk density of HB2-PC-T0-P0 may be partially attributed to its having sugar maple as its major species composition versus trembling aspen for HB1-CC-T0-P0 and HB3-CC-T0-P0. Sugar maple has a higher basic specific gravity (0.6) than trembling aspen (0.4; Jessome 1977). Another possible explanation for the relatively high bulk density of HB2-PC-T0-P0 compared with the other two samples is the fact that this biomass is composed of tops and branches only. Researchers have found that the density of branch wood can be more than twice as high as stem wood density (Gryc and Horacek 2007, Dibdiakova and Vadla 2012). However, other researchers have found that tops and limbs are pliable and tend to produce large-sized material on comminution (Hakkila and Parikka 2002, Mckendry 2002, Basu 2010); large-sized chips increase the diagonal-to-thickness ratio and the bulk volume and thus should decrease the bulk density.

Table 2.—Percent moisture content (MC) and bulk density of forest residue samples.^a

| | MC, wet (%) | Bulk density, wet (kg/m ³) | Bulk density, dry (kg/m ³) |
|-------------------|----------------|---|---|
| Harvest block | | | |
| HB1-CC-T0-P0 | 40.1 (1.6) A | 106.3 (11.4) A | 98.6 (15.2) A |
| HB2-PC-T0-P0 | 47.5 (0.4) B | 288.6 (19.1) B | 136.6 (5.9) B |
| HB3-CC-T0-P0 | 40.3 (1.2) A | 241.9 (7.1) C | 109.8 (3.8) A |
| Time and position | | | |
| HB3-CC-T1-P1 | 28.9 (2.6) X | 180.2 (6.5) X | 108.8 (6.4) X |
| HB3-CC-T1-P2 | 67.8 (0.6) Y | 395.8 (30.2) Y | 134.6 (10.4) Y |
| HB3-CC-T2-P1 | 19.3 (0.6) Z | 177.3 (21.6) X | 94.0 (11.4) X |
| HB3-CC-T2-P2 | 73.1 (3.2) Y | 423.2 (31.1) Y | 117.4 (8.7) XY |

^a Values are means (standard deviations in parentheses); *n* = 3. Forest residue samples with the same letter (by column) do not differ statistically (Tukey test, *P* > 0.05).

A 2-way ANOVA showed that both time and position significantly affected the dry bulk density of forest residue samples, with position having a greater impact. The bulk density of forest residues decreased over storage time and may be attributed to biological and/or chemical degradation of the biomass (Ashton et al. 2007, Afzal et al. 2010). The higher bulk densities of the biomass inside the pile compared with the surface material can be attributed to movement of smaller-sized chips farther into the pile through a natural settling process caused by rain and wind (Hakkila and Parikka 2002). If the small particles filter into the pile over time, they will result in a higher compaction of the pile and greater overall bulk density. Piling of biomass has a favorable impact on bulk density, but there may be an optimum point at which material degradation balances with compaction.

The generally low dry bulk densities of all forest residue samples may be attributed to the relationship between pliable tops and limbs and their tendency to produce large-sized material on comminution, thus decreasing the bulk density. The inverse proportionality of chip size on bulk density was confirmed in this study, as all isolated large fractions had lower bulk densities compared with their respective small fractions (Table 3).

Wood/bark ratio.—The wood/bark ratio of forest residue samples can be used as a guide in choosing an application that will optimize value. For instance, a forest residue sample that is composed mainly of wood can be used for fiber applications, whereas if the material contains a high percentage of bark, it may be useful for isolation of phenolic compounds. In addition, the wood/bark ratio can give an idea of the thermochemical properties of forest residues; forest residues composed mainly of bark will be expected to have a slightly higher heating value, while another with a high percentage of wood will be expected to be more reactive and burn “cleaner.”

The percentage of wood, bark, and fines in all forest residue samples were determined except for forest residues sampled after 2 years of storage (Table 4). The mass fractions of wood in the three initial samples were statistically the same, indicating that there is no difference between biomass sourced from tops and limbs only (Block 2) versus biomass from tops and branches and whole trees (Blocks 1 and 3) in this study. The wood component in the forest residue samples ranged from 63 percent for HB3-CC-T1-P2 to 84 percent for HB1-CC-T0-P0. The amount of fines created by the grinder was much greater for the Rotochopper B66 used on Blocks 2 and 3 than the Rotochopper MC266 used on Block 1. This may be attributed to the design and function of the grinding

Table 3.—Bulk density of fractions of forest residue samples.^a

| | Bulk density, oven-dry basis (kg/m ³) | |
|--------------|---|----------------|
| | Large fraction | Small fraction |
| HB1-CC-T0-P0 | 76.1 (8.0) | 80.6 (9.7) |
| HB2-PC-T0-P0 | 136.8 (8.5) | 141.8 (2.2) |
| HB3-CC-T0-P0 | 113.7 (8.8) | 135.9 (9.1) |
| HB3-CC-T1-P1 | 96.0 (4.4) | 115.6 (2.5) |
| HB3-CC-T1-P2 | 92.6 (5.3) | 135.3 (4.3) |
| HB3-CC-T2-P1 | 97.9 (8.4) | 110.8 (4.8) |
| HB3-CC-T2-P2 | 105.4 (9.6) | 112.3 (7.7) |

^a Values are means (standard deviations in parentheses); *n* = 3.

Table 4.—Wood/bark ratio (oven-dry basis) of forest residue samples.^a

| | % wood | % bark | % fines |
|---------------|--------------|--------------|--------------|
| Harvest block | | | |
| HB1-CC-T0-P0 | 83.9 (3.3) A | 16.1 (3.3) A | |
| HB2-PC-T0-P0 | 77.5 (2.3) A | 11.9 (5.7) A | 10.6 (3.5) A |
| HB3-CC-T0-P0 | 80.4 (1.7) A | 9.6 (4.6) A | 10.0 (2.9) A |
| Position | | | |
| HB3-CC-T1-P1 | 79.1 (1.3) X | 15.7 (0.7) X | 5.2 (1.9) X |
| HB3-CC-T1-P2 | 63.2 (2.1) Y | 17.6 (2.9) X | 19.2 (0.8) Y |

^a Values are means (standard deviations in parentheses); *n* = 3. Forest residue samples with the same letter do not differ statistically (Tukey test, *P* > 0.05).

equipment, but further conjecture is beyond the scope of this study.

The movement of smaller-sized materials into the pile over time resulted in a decrease in the amount of fines on the surface and a significantly higher amount of fines within the pile. In addition, biological and/or chemical degradation might reduce the overall size distribution to create a higher mass fraction of fines. The opposite effect is observed in HB3-CC-T1-P1, which was sampled from the surface of the pile.

Thermochemical characteristics

Ultimate analysis.—Elemental composition can be used to calculate the atomic ratios of the elements in the biomass. Carbon content of a fuel positively correlates with its HHV, and a high proportion of hydrogen suggests that the fuel will be more reactive and will yield a higher volatile fraction when combusted. While a low oxygen-to-carbon ratio in a fuel results in a higher HHV, it also gives rise to higher CO₂ emission per unit of energy produced. Furthermore, the quantity of chlorides in forest residue samples was investigated because they can potentially react with potassium and sodium to form alkali chlorides. Fouling and slagging in a boiler can result when these inorganic particles deposit on the surface (Hakkila and Parikka 2002, Basu 2010).

Elemental composition results are presented in Table 5. No nitrogen was detected in the samples tested at a 0.3 percent detection limit.

As with most wood, the ultimate analysis of the forest residue samples was very consistent. The percent C in all forest residue samples averaged 51.2 (standard deviation [SD] = 0.9), percent H averaged 5.7 (SD = 0.1), and percent O averaged 43.1 (SD = 1.0). Ultimate analysis results of

Table 5.—Elemental composition (oven-dry basis) of forest residue samples.^a

| | % carbon | % hydrogen | % oxygen | Chlorides |
|--------------|----------|------------|----------|-------------|
| | | | | (ppm) |
| HB1-CC-T0-P0 | 51.7 | 5.9 | 42.5 | 286 (73) A |
| HB2-PC-T0-P0 | 49.7 | 5.7 | 44.6 | 178 (138) A |
| HB3-CC-T0-P0 | 51.3 | 5.6 | 43.1 | 274 (50) A |
| HB3-CC-T1-P1 | 52.0 | 5.9 | 42.1 | 154 (4) A |
| HB3-CC-T1-P2 | 51.1 | 5.7 | 43.2 | 150 (50) A |

^a Values are means (standard deviations in parentheses); *n* = 3 for chlorides. Forest residue samples with the same letter do not differ statistically (Tukey test, *P* > 0.05).

heterogeneous forest residue from the various sites, harvesting scenarios, and storage regimes corresponded closely with data for biomass reported in literature, with the percentages of C, H, and O in the dry weight of biomass reported to range from 41 to 56, 5 to 7, and 35 to 45, respectively (Mckendry 2002, Basu 2010).

Small amounts of chlorides were found in the forest residue samples, averaging 208 ppm (milligrams per oven-dry kilogram of sample; Table 5). No statistically significant differences were found among the samples. Chlorides contained in forest biomass have been reported in Vassilev et al. (2010) to vary between 100 and 900 ppm. Chloride content is influenced by the time of the harvest, with late season harvesting generally resulting in reduced levels of chlorine because of translocation from the leaves to the roots. There does appear to be an indication of a reduction in the chloride concentration in the biomass on storage, even though the values are not statistically different. This can be a result of the leaching of water-soluble chloride compounds by rain or dew permeating through the storage pile (Bakker and Elbersen 2005).

Thermal properties.—Important thermally related properties of the forest residue samples can be determined through proximate analysis. Amounts of volatiles, char, and ash give an indication as to the suitability of the fuel for utilization in different technologies.

The mass of volatile matter, fixed carbon, and ash determined by proximate analysis were expressed as percentage of a moisture-free mass (Table 6).

The proximate analysis revealed some significant differences between the various samples. For example, the forest residue from Block 2 (selection cut) had the highest amount of ash and also lowest volatile matter of the three sites. Obernberger et al. (2006) and Acquah et al. (2015) reported ash values of 1.5 and 1.4 percent dry basis from deciduous and coniferous logging residues, respectively. These values compare closely with Blocks 1 and 3 (clear-cut). It is believed that operational practices may have led to higher ash content of the forest residue in Block 2 (selection cut). In this operation, a skidder was used to push the biomass into piles. Rock and dirt contamination was noted, and some of the biomass could not be processed through the grinder because of this. Also, in Block 1, the biomass was ground directly into vans, whereas in Blocks 2 and 3, the biomass was comminuted and piled directly on the ground, leading to a greater likelihood of dirt contamination of the biomass. Ash formed from incombustible minerals in lignocellulosic biomass detracts from the available

energy, influences the overall cost of processing, and creates greater concern for particulate emissions.

Considering the effect of time and position on the thermal properties of forest residue samples, the differences in percent ash of stored forest residues were not statistically significant but were higher than the initial ash content. Storage has been found to result in an apparent increase in ash as a result of dry matter loss (White et al. 1986, Andersson et al. 2002). In fact, even the ash content of clean stored hardwood chips was found to increase from 1.2 to 2 percent after 50 weeks of storage (White et al. 1986).

The 2-way ANOVA showed that position, as well as the synergistic effect of time and position, significantly affected the percent volatile matter of forest residues. For the percentage of fixed carbon in forest residues, time did have an influence as well. A possible explanation for the decrease in volatile matter and increase in percent fixed carbon of stored forest residues is that chemical and/or biological degraders mostly attacked the sugar-based polymers in wood, such as the hemicelluloses, leaving behind the lignin, thus forming a more recalcitrant product high in carbon (Fengel and Wegener 1984, Makela et al. 2014).

Energy value.—The HHVs, the maximum amount of energy that could be potentially recovered on complete combustion for forest residue samples, are given in Table 7.

The HHV of all forest residue samples characterized in this study averaged 19.0 MJ/kg with an SD of 0.3 MJ/kg. According to Ragland et al. (1991) and Senelwa and Sims (1999), the HHV of the wood of different tree species varied by less than 15 percent, with larger variations reported for bark and leaves. It is therefore worth mentioning that the HHV of forest residues that were composed of several species and different tree components varied by less than 2 percent. The HHV of HB3-CC-T0-P0, which was composed of about equal volumes of hardwoods and softwoods, was expected to be slightly higher than the HHV's of HB1-CC-T0-P0 and HB2-PC-T0-P0, which were made up of only hardwoods; as softwoods are known to typically have higher extractives and lignin content and thus have higher energy value (Fengel and Wegener 1984, Klass 1998, Mckendry 2002, Demirbas and Demirbas 2009). However this was not the case in this study.

There was very little difference in the HHV with respect to time of storage or position in the pile. However, it does appear that the HHV did increase on storage from 18.7 to over 19 MJ/kg for all but one of the stored samples (Table

Table 6.—Proximate analysis (oven-dry basis) of forest residue samples.^a

| | % volatile matter | % fixed carbon | % ash |
|-------------------|-------------------|----------------|-------------|
| Harvest block | | | |
| HB1-CC-T0-P0 | 83.0 (0.2) A | 15.1 (0.1) A | 1.9 (0.3) A |
| HB2-PC-T0-P0 | 80.3 (0.5) B | 15.0 (0.5) A | 4.7 (0.8) B |
| HB3-CC-T0-P0 | 82.4 (0.7) A | 15.9 (0.1) B | 1.7 (0.7) A |
| Time and position | | | |
| HB3-CC-T1-P1 | 82.9 (0.4) X | 14.5 (0.4) X | 2.6 (0.6) X |
| HB3-CC-T1-P2 | 79.3 (0.7) Y | 17.8 (0.5) Y | 2.9 (0.4) X |
| HB3-CC-T2-P1 | 80.6 (1.2) Y | 16.9 (1.1) Y | 2.5 (0.2) X |
| HB3-CC-T2-P2 | 80.0 (0.5) Y | 18.2 (0.2) Y | 1.9 (0.3) X |

^a Values are means (standard deviations in parentheses); $n = 3$. Forest residue samples with the same letter (by column) do not differ statistically (Tukey test, $P > 0.05$).

Table 7.—Higher heating values (HHVs) of forest residue samples.^a

| | HHV (MJ/kg) | HHV, ash free (MJ/kg) |
|-------------------|--------------|-----------------------|
| Harvest block | | |
| HB1-CC-T0-P0 | 18.8 (0.2) A | 19.2 (0.2) A |
| HB2-PC-T0-P0 | 19.0 (0.2) A | 19.9 (0.2) B |
| HB3-CC-T0-P0 | 18.7 (0.1) A | 19.0 (0.1) A |
| Time and position | | |
| HB3-CC-T1-P1 | 19.4 (0.2) X | 19.9 (0.2) X |
| HB3-CC-T1-P2 | 18.6 (0.0) Y | 19.1 (0.0) Y |
| HB3-CC-T2-P1 | 19.1 (0.3) X | 19.5 (0.3) X |
| HB3-CC-T2-P2 | 19.4 (0.1) X | 19.8 (0.1) X |

^a Values are means (standard deviations in parentheses); $n = 3$. Forest residue samples with the same letter (by column) do not differ statistically (Tukey test, $P > 0.05$).

Table 8.—Effect of bulk density and moisture content (MC) on heat values of forest residue samples.

| | % MC | Bulk density, wet (kg/m ³) | Net heat value (MJ/kg) | Energy density (MJ/m ³) |
|--------------|------|--|------------------------|-------------------------------------|
| HB1-CC-T0-P0 | 40.1 | 106.3 | 10.2 | 1,079.9 |
| HB2-PC-T0-P0 | 47.5 | 288.6 | 8.7 | 2,496.8 |
| HB3-CC-T0-P0 | 40.3 | 241.9 | 10.0 | 2,426.7 |
| HB3-CC-T1-P1 | 28.9 | 180.2 | 13.0 | 2,340.6 |
| HB3-CC-T1-P2 | 67.8 | 395.8 | 4.1 | 1,614.5 |
| HB3-CC-T2-P1 | 19.3 | 177.3 | 14.8 | 2,631.2 |
| HB3-CC-T2-P2 | 73.1 | 423.2 | 3.2 | 1,346.4 |

8). In a similar study by Afzal et al. (2010), they also noted no significant changes in HHV of white birch biomass stored in various forms (i.e., wood chips, bundles, and slash piles) over a period of 1 year.

Moisture (both the inherent water of constitution and acquired moisture) reduces the potential energy of lignocellulosic biomass through the loss of energy as latent heat of vaporization. Inherent moisture reduces the HHV to the LHV, while acquired moisture reduces the HHV to the NHV. The negative effects of moisture and ash on the potential recoverable energy is shown in Figure 5. It should be noted that the HHV on an ash-free basis, of the very heterogeneous samples, is very consistent.

Furthermore, because biomass is transported, stored, and sometimes sold on a volumetric basis, it is important that the energy of a truckload of fuel also be known. The energy densities (a measure of the amount of energy per unit volume of fuel in megajoules per cubic meter) of

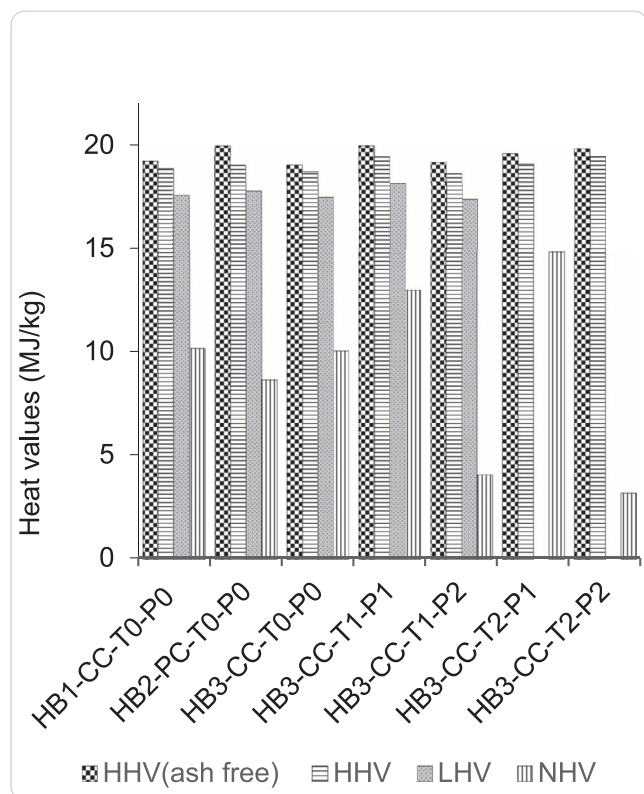


Figure 5.—Effect of moisture and ash on potential energy of forest residue fuels. HHV, LHV, and NHV = higher, lower, and net heating values, respectively.

forest residues are presented together with their corresponding initial MCs and wet bulk densities in Table 8. The energy densities of the samples averaged 1,991 MJ/m³ (SD = 628).

Biomass fractionation

Biomass fractionation was explored as a means of adding value to the heterogeneous forest residues by generating more homogeneous materials that may be better suited for specific end uses. To determine the impact of fractionation, a comparative study of specific physical and thermochemical properties was performed on large and small fractions of forest residues.

The wood/bark ratio was determined for the large and small fractions of all forest residues samples except for HB3-CC-T2-P1 and HB3-CC-T2-P2. Results showed the large fractions to have significantly higher amounts of wood (mean = 92%; SD = 2%) compared with their respective small fractions (mean = 64%; SD = 5%), and all of the small fractions except for HB1-CC-T0-P0 had significantly more bark (mean = 20%; SD = 3%) than wood (Table 9).

Even though there were differences in the percentages of wood and bark in the two fractions, these differences were not significant enough to impact their overall elemental composition (Table 10). However, 0.4 and 0.5 percent of nitrogen was detected in the small fractions of HB1-CC-T0-P0 and HB3-CC-T1-P2, respectively. Nitrogen was not detected in any other sample.

Proximate analysis of the fractions showed all the large fractions to have significantly higher percentages of volatile matter compared with the small fractions, whereas the small fractions had significantly higher amounts of ash compared with their respective large fractions (Table 11). This higher amount of ash in the small fraction can possibly be attributed to higher amounts of soil, leaves, and bark in that biomass. However, it is worth mentioning that the ash contents of all forest residue samples determined in this study were relatively low and met Pellet Fuel Institute (PFI) ash specifications for standard pellets, which allow up to 6 percent ash in certain pellet grades (PFI 2010).

On examination, there seemed to be a directly proportional relationship between the amount of wood and the volatile matter yield of forest residues. A scatterplot of the percentage of wood against the percentage of volatile matter proved this, with an $r^2 = 0.53$ and $P < 0.001$ (Fig. 6).

On the other hand, even though bark and/or fines are generally known to produce more ash on combustion because they are more prone to contamination, this was not observed in this study. Scatterplots of percent bark and/or percent fines versus percent ash gave P values greater than 0.05. However, the amount of bark and fines alone did appear to influence the percent fixed carbon (bark and fines: $r^2 = 0.6$, $P < 0.001$; fines: $r^2 = 0.7$, $P < 0.001$). A possible explanation of these results is the relatively higher amount of extractives in the bark as well as the fines being the result of brown rotters that degraded holocelluloses to leave a recalcitrant product high in lignin.

Finally, the HHVs of the large and small fractions were very similar. The mean HHV for the large fractions was

Table 9.—Wood/bark ratio (ovendry basis) of original and fractions of forest residue samples.^a

| | % bark | | | % wood | | | % fines | |
|--------------|-----------------|----------------|----------------|-----------------|----------------|----------------|-----------------|----------------|
| | Original sample | Large fraction | Small fraction | Original sample | Large fraction | Small fraction | Original sample | Small fraction |
| HB1-CC-T0-P0 | 16.1 (3.3) | 9.5 (4.5) | 20.2 (2.5) | 83.9 (3.3) | 90.5 (4.5) | 79.8 (4.5) | — | 12.3 (5.0) |
| HB2-PC-T0-P0 | 11.9 (2.3) | 7.8 (1.9) | 21.8 (2.7) | 77.5 (5.7) | 92.2 (1.9) | 78.2 (3.6) | 10.6 (3.5) | 26.5 (6.0) |
| HB3-CC-T0-P0 | 9.6 (1.7) | 4.1 (0.0) | 23.9 (2.1) | 80.4 (4.6) | 95.9 (0.0) | 76.1 (3.1) | 10.0 (2.9) | 12.9 (3.1) |
| HB3-CC-T1-P1 | 15.7 (1.3) | 8.8 (4.3) | 25.9 (2.0) | 79.1 (0.7) | 91.2 (4.3) | 74.1 (3.6) | 5.2 (1.9) | 16.3 (1.8) |
| HB3-CC-T1-P2 | 17.6 (2.1) | 8.1 (1.7) | 27.6 (2.2) | 63.2 (2.9) | 91.9 (1.7) | 72.4 (3.0) | 19.2 (0.8) | 10.7 (4.0) |

^a Values are means (standard deviations in parentheses); *n* = 3.

Table 10.—Ultimate analysis (ovendry basis) of fractions of forest residue samples.

| | % carbon | | % hydrogen | | % oxygen | |
|--------------|----------------|----------------|----------------|----------------|----------------|----------------|
| | Large fraction | Small fraction | Large fraction | Small fraction | Large fraction | Small fraction |
| HB1-CC-T0-P0 | 51.8 | 50.0 | 5.8 | 5.8 | 42.3 | 43.9 |
| HB2-PC-T0-P0 | 51.1 | 51.3 | 5.8 | 5.7 | 43.1 | 43.1 |
| HB3-CC-T0-P0 | 51.1 | 51.3 | 5.8 | 5.7 | 43.1 | 43.1 |
| HB3-CC-T1-P1 | 51.2 | 51.4 | 5.9 | 5.8 | 42.9 | 42.8 |
| HB3-CC-T1-P2 | 52.0 | 50.3 | 5.9 | 6.0 | 42.1 | 43.2 |

Table 11.—Proximate analysis (ovendry basis) of fractions of forest residue samples.^a

| | % volatile matter | | | % ash | | |
|--------------|-------------------|----------------|----------------|-----------------|----------------|----------------|
| | Original sample | Large fraction | Small fraction | Original sample | Large fraction | Small fraction |
| HB1-CC-T0-P0 | 83.0 (0.2) | 86.1 (0.3) | 81.1 (0.6) | 1.9 (0.3) | 0.9 (0.0) | 3.0 (0.3) |
| HB2-PC-T0-P0 | 80.3 (0.5) | 84.8 (0.4) | 80.1 (0.5) | 4.7 (0.8) | 1.5 (0.8) | 3.5 (0.4) |
| HB3-CC-T0-P0 | 82.4 (0.7) | 84.7 (0.4) | 79.4 (0.5) | 1.7 (0.7) | 0.9 (0.3) | 4.5 (0.3) |
| HB3-CC-T1-P1 | 82.9 (0.4) | 84.5 (0.3) | 82.4 (0.2) | 2.6 (0.6) | 0.9 (0.1) | 2.2 (0.4) |
| HB3-CC-T1-P2 | 79.3 (0.7) | 83.1 (0.4) | 78.5 (0.6) | 2.9 (0.4) | 1.1 (0.0) | 3.1 (0.5) |
| HB3-CC-T2-P1 | 80.6 (1.2) | 83.3 (1.4) | 79.0 (0.9) | 2.5 (0.2) | 1.4 (0.5) | 2.6 (0.3) |
| HB3-CC-T2-P2 | 80.0 (0.5) | 82.3 (1.9) | 74.7 (1.2) | 1.9 (0.3) | 1.8 (0.3) | 4.8 (1.5) |

^a Values are means (standard deviations in parentheses); *n* = 3.

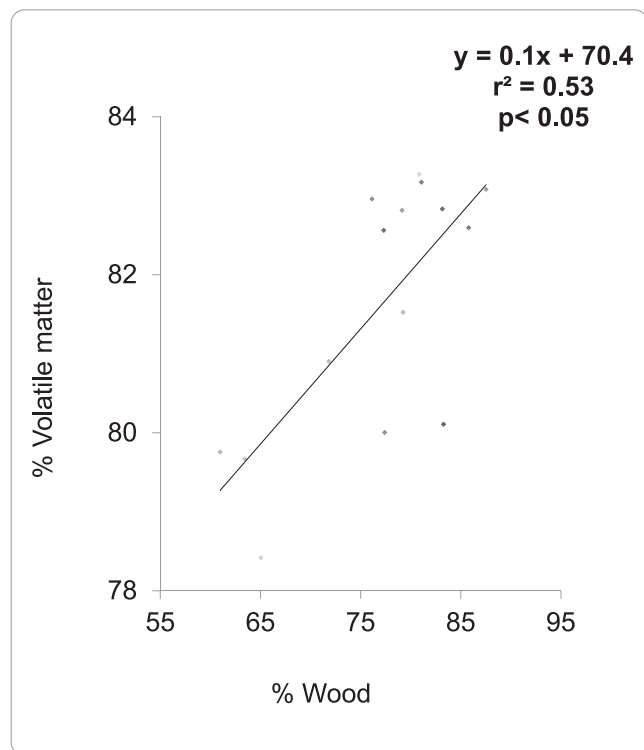


Figure 6.—Correlation between percent wood component and percent volatile matter content.

18.7 MJ/kg (SD = 0.2), while that of the small fractions was 19.0 MJ/kg (SD = 0.6).

Conclusions and Recommendations

This study highlighted some of the important characteristics of heterogeneous forest residues that will influence their utilization. MC of the fresh mixed forest residues, which is of prime importance in energy applications, was higher than it would be for bole wood alone, varying between 67 and 89 percent (ovendry basis), suggesting that higher proportions of branches and foliage will result in higher initial MC of the material. If harvested in the spring and summer seasons, the forest harvest biomass would benefit from piling and storage prior to chipping. Transpirational drying has been proven to be an effective means of reducing MC in this type of material, and it could remain in its original form, on-site, for a few days to achieve a significant reduction in moisture. Once the biomass is chipped and piled, the MC becomes much more variable. Variability in properties such as MC and bulk density is much more difficult to deal with in industrial processes than either low energy content or low bulk density; hence, any pretreatment that will reduce variability in the material is beneficial. The variability of these two qualities and their influence on the energy density of the forest residue biomass is significant and was found to vary from 1,346 to 2,631.2 MJ/m³.

The HHVs of the forest residue materials, whether fresh or subjected to 2 years of storage, were very similar, ranging

from 19.0 to 19.9 MJ/kg (ash free). Larger variations are detected when MC is taken into consideration (NHV), with the wettest biomass having only 3.2 MJ/kg and the driest 14.8 MJ/kg. Again, the effect of storage on the variability of biomass is noteworthy, as both these materials were found in the same pile after the same storage time. However, storage did provide some beneficial changes to the quality of the forest residues in that an increase in bulk density was observed and levels of chlorides may potentially be reduced.

Finally, attempts to homogenize the forest residue through a straightforward fractionation process did lead to fractions that had different characteristics and properties and could potentially be used for higher-value applications.

Acknowledgments

The authors would like to thank the Mazinaw-Lanark Forest Inc. and the Eastern Ontario Model Forest for coordination of the operational harvesting trails.

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