Fuel Properties of Sugar Maple and Yellow Birch Wood in Relation with Tree Vigor

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The fuel properties of wood obtained from sugar maple (SM) and yellow birch (YB) of temperate hardwood stands located in the Province of Québec, Canada were studied to see how tree vigor affects the chemical composition and calorific value of the wood. This study focused on the physical and chemical properties of wood with the aim of using the material for the production of solid biofuels. Specific items measured included the wood's calorific values, and the levels of extractives, ash, and lignin. Changes in chemical composition were found among tree vigor classes. The low vigor trees had higher extractives, ash, and lignin contents than the vigorous trees. Total extractives ranged between 4.88 and 7.32% in SM, and between 3.35 and 5.12% in YB. Klason lignin ranged between 21.46 and 23.53% in SM, and between 18.60 and 21.51% in YB. Ash content ranged between 0.38 and 0.97% in SM, and between 0.26 and 0.47% in YB. The combined effects of higher lignin content that could contribute to a better self-bonding of particles and of higher extractives content that could facilitate the pelletization process makes the low vigor trees more suitable for conversion into solid biofuels. The higher amounts of extractives and lignin present in the low vigor sugar maple and yellow birch trees could also have a positive role in maintaining the high calorific values of this wood despite higher ash content.

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INTRODUCTION

In recent years, a clear interest has arisen for the use of forest biomass as a biofuel. This is mainly motivated by the low environmental impact and low carbon emissions resulting from the use of forest biomass as a source of energy. Also, it may not be achievable to meet the global increase in energy consumption without the contribution of biofuels (Hunt 2009; Demirbas 2010; Masia *et al.* 2010).

The most important characteristic of a biofuel is its energy content (Lestander 2013). The standard measure of the energy content of a fuel is its higher heating value (HHV), which is sometimes called the calorific value or the heat of combustion (Jenkins *et al.* 1998). It may be expressed as either the higher heating value (also known as the gross calorific value) or the lower heating value (also known as net calorific value). The CEN/TS 14588 (2003) standard defines calorific or heating value as the quantity of energy released per unit mass or volume of a material upon complete combustion. Heating value is the most fundamental property in connection with fuel quality, and it is therefore widely used as a mean to compare different types of fuels or feedstocks.

The heating value of woody materials is directly related to its chemical composition. The calorific value of moisture-free wood is approximately 18 to 21 MJ/kg, depending on the tree species (Schobert 2013). Because lignin has a higher amount of energy per unit mass than cellulose (26 and 18 MJ/kg, respectively), the calorific value varies with the lignin content, and to a much greater extent, with the resin content (Wang *et al.* 1982; White 1987; Moya and Tenorio 2013). Studies were performed to determine the relationships between the chemical composition (hemicellulose, cellulose, and lignin) of woody biomass and its HHV. No direct relation between the hemicellulose and cellulose content of a biomass and its HHV was reported (Demirbas 2005). However, a highly significant linear correlation was found between the HHV and lignin content within a biomass (White 1987; Demirbas 2001; Demirbas 2005; Telmo and Lousada 2011).

Inorganic minerals (ashes) are noncombustible, and their presence in wood has an adverse effect on the heating value (Wang *et al.* 1982; Kataki and Konwer 2001; Demirbas 2002; Moya and Tenorio 2013; Schobert 2013). The ash content of biomass varies in a broad range from around 0.5% (dry basis (d.b.)) for some clean woody biomasses to 12% (d.b.) for straws and cereals; these ash values can be even higher if the fuel is contaminated with mineral impurities (van Loo and Koppejan 2008).

The chemical composition in the tree stems differs from that in the branches, knots, tops, and roots. Marked variations were also observed within a stem, especially in the radial direction from juvenile to mature wood, and from heartwood to sapwood (Barnett and Jeronimidis 2003). Differences between reaction wood and normal wood were also reported (Sjöström and Alén 1999). Generally, the lignin content of hardwoods varies in the range of 16 to 24%. These estimates are based on Klason lignin content (acid-insoluble lignin) determined without accounting for the acid-soluble lignin.

Acid-soluble lignin is low molecular weight lignin that is solubilized in the acidic hydrolysis solution. Inclusion of acid soluble lignin concentration in the total lignin value is necessary, as acid soluble lignin can represent an important portion of lignin, especially in hardwoods (Sluiter and Sluiter 2011). The available data on within tree variation suggest that the lignin content of sapwood is equal to or slightly higher than that of the heartwood, higher in juvenile wood than in mature wood, and lower in tension wood than in normal wood. In many species, lignification of the wood tissue is nearly completed during the year of formation in the cambial zone (Sarkanen and Ludwig 1971).

Woody biomass could be considered as a potential renewable energy source with supplementary value-added applications depending on its chemical composition variation (Lindsey *et al.* 2013; Sengupta and Pike 2013; St-Pierre *et al.* 2013). Wood extractives can have many uses as natural dyes for fabrics, foods and cosmetics, as well as potential medicines. These materials are receiving increased attention as low-volume but high-value products (Lavoie and Stevanovic 2005; Rossi *et al.* 2013). These extractives could be recovered before using wood as a fuel. Thus, it is of interest to study the effect of extractive removal on the calorific value of wood. The extractive compounds in wood can be grouped in two main types: lipophilic (soluble in organic solvents) and hydrophilic (water-soluble).

The constituents of lipophilic extractives include terpenoids and steroids, fats, waxes, and phenolic compounds that consist of stilbenes, lignans, tannins, and different classes of flavonoids. Fats are known as an energy source for parenchyma cells, whereas terpenoids and phenolics protect the tree against microorganism attacks (Sjöström 1993; Sjöström and Alén 1999).

Over the past decades, the most valuable tree stems within the Eastern hardwood forests in North America, sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britton), have been harvested for the production of hardwood lumber (Nyland 1992; Bédard and Majcen 2003; Pothier *et al.* 2013). Thus, the current forests contain a large proportion of non-vigorous trees of very little or no commercial value (Havreljuk *et al.* 2014).

From the forest management standpoint, the presence of these low vigor and quality stems has a negative effect on forest health and value. Therefore, in the partial cuts typically applied to such stands, harvesting priority is now given to the non-vigorous trees while leaving the more vigorous trees to grow for future harvest (Delisle-Boulianne *et al.* 2014).

To determine tree vigor in the field prior to harvesting, the tree vigor classification system proposed by Boulet (2007) has been applied to hardwood stands in the Province of Québec, Canada. This evaluation is based on pathological symptoms (*e.g.*, presence of cankers and fungi), mechanical defects (*e.g.*, cracks, leaning) and other visible features (*e.g.*, trunk splits, defoliation).

Healthy trees have several defense mechanisms against fungal infection. However, when a tree is wounded or otherwise weakened by living organisms, especially fungi, its chemical composition may change (Jane *et al.* 1970; Stokland *et al.* 2012). According to Barnett and Jeronimidis (2003), the occurrence of physical wounds, mechanical stress, or attack by biotic organisms induces many trees to produce traumatic tissues, and to synthesize and deposit protecting compounds in the affected areas. Most of these compounds are extractives and appear in high amounts in the affected parts of the wood.

Fungal attack has been found to be associated with the increase in lignin content because of its resistance to degradation by pathogens, as reported by Hawkin and Boudet (2003) for cider gum (*Eucalyptus gunnii*). Increases in extractive content following fungal attack was also reported by Barry *et al.* (2001) for shining gum (*Eucalyptus nitens*).

To the best of the authors' knowledge, there are no reports in the literature on the effect of tree vigor on the calorific value of wood. In addition, the assessment of chemical composition and fuel characteristics of the biomass is important for the efficient utilization and conversion of the feedstock into biofuels and chemicals. Therefore, the aim of the present work was to determine the changes in chemical composition and calorific value of wood related to tree vigor for both sugar maple and yellow birch.

Because the current work was conducted with the intention of using the material for the production of solid biofuels with supplementary value-added applications, the investigation was focused on the determination of extractives, ash, and lignin content of wood, and the measurement of calorific values of both extracted and non-extracted wood samples.

EXPERIMENTAL

Materials and Sample Preparation

Tree sampling was carried out in July 2010 at two degraded hardwood stands composed mainly of sugar maple and yellow birch. The stands were located in the vicinity of Mont-Laurier, Québec, Canada (46°39'40"N, 75°36'30"W and 46°39'05"N, 75°36'25"W). The trees were classified according to the tree vigor (MSCR) classification system proposed by Boulet (2007) and described as follows. Trees of reserve stock (class R) are free of any symptoms of disease or damage and are considered as healthy trees with the highest probability of survival. Growing trees (class C) have minor defects but are not biologically declining and are expected to survive until the next harvest without risk of imminent wood decay. Low quality or defective trees (class S) are considered to be declining in terms of vigor, wood quality, and volume increment, and are not expected to survive until the next harvest. Finally, moribund trees (class M) show signs of either lethal pathological infection or severe damage with high risk of trunk breakage. Moribund trees are biologically declining and are assumed to have a high probability of mortality before the next scheduled harvest.

After classifying each tree according to its vigor class, 18 sample trees (9 sugar maple trees and 9 yellow birch trees) were selected and cut (Table 1). The selected trees were assigned to one of the 3 following categories: R - vigorous (healthy) tree, S - weakened (defective) tree, and M - moribund (dying) tree. Figure 1 presents the visual appearance of representative sample trees and their wood showing advanced biodeterioration (sap-staining fungi and/or wood rotting fungi) of wood of the less vigorous trees.

Table 1. Description of the 18 Sample Trees Used for Chemical Analysis

Tree vigor *	Type of defect/ Characteristics/ Description	DBH (cm)	
		Sugar maple	Yellow birch
Healthy tree (R class)	Green foliage and without wounds	30.0	33.5
		29.3	27.1
		35.0	31.8
Weakened tree (S class)	Wounds, poor foliage (defoliation), presence of sap-staining fungi	39.5	36.8
		31.3	30.8
		36.3	43.7
Dying tree (M class)	Partial bark lose or fallen off, presence of decay/ wood rotting fungi (fungal infection)	37.9	33.7
		27.2	40.0
		31.3	31.4

DBH= Diameter at breast height of tree stem measured under bark at 1.3 m from the root collar, *The assignment of each tree to a vigor class in the field was based on a visual assessment of tree morphological characteristics. Trees were classified according to MSCR classification system proposed by Boulet (2007).

Fig. 1. Visual appearance of healthy (left), weakened (middle) and dying/moribund (right) sugar maple trees (above), and corresponding wood (below) showing healthy wood (left), early stage stained wood (middle), and stained wood associated with decay (right).

After the trees were felled, measured and marked, a sample log (of about 60 cm long) was extracted from each sample tree at a distance of approximately 70 cm from the root collar. It was then wrapped in plastic bags, transported to the Renewable Materials Research Center, Laval University, Québec, Canada, and then stored at -5 °C in a laboratory freezer to avoid enzyme-induced changes and oxidation of the extractives (Sjöström and Alén 1999; St-Pierre *et al.* 2013).

Analyses in the present study were conducted only for the disks sectioned from sample logs. The bark was then removed from the disks. The wood material was converted into chips, dried at 30 °C for approximately 48 h, and milled. The coarse material was ground in a centrifugal mill (Pulverisette 19 grinder, Fritsch, Germany). The wood flour was sieved through 40 mesh (425 μm) and 60 mesh (250 μm) screens. After grinding and sieving, the samples were kept in closed polyethylene bags and stored at -5 °C in a laboratory freezer until further analyses.

Determination of Chemical Properties

Ash content, extractive content in an ethanol-toluene mixture, and extractive content in hot water were determined in accordance with ASTM D1102-84, ASTM D1107-96 and ASTM D1110-84 (method B - hot water solubility) standards, respectively. When wood is treated with strong acids, the carbohydrates are hydrolyzed and an insoluble residue is obtained; this insoluble residue is the acid-insoluble lignin (Klason lignin). Because some of the wood extractives would remain with the insoluble lignin during the hydrolysis, these extractives were first removed from the wood by solvent extraction. In the present study, acid-insoluble lignin was determined in

accordance to the ASTM E1721-01 standard. The chemicals used include ethanol (anhydrous grade) from Commercial Alcohols Inc. (Canada), toluene and 72% sulfuric acid (A.C.S grade) from VWR International (Canada). Acid-soluble lignin was analyzed within 4 h of the hydrolysis process using UV-Vis absorption spectroscopy (Varian, Cary 50 UV-Vis, Varian Inc., Australia) at 205 nm. Three replicates were performed for each test sample and the mean values were used for statistical analyses.

Determination of the Calorific Value

The gross calorific value (GCV), or higher heating value (HHV), represents the absolute value of the specific energy of combustion per unit mass of a solid biofuel burned in oxygen in a calorimetric bomb under specified conditions. In the present study, the HHV was determined in accordance to the CEN/TS 14918:2005 standard. The samples were combusted in a Parr 6400 Automated Isoperibol calorimeter (Parr Instrument Company, Illinois, USA). The calorimeter was calibrated with a benzoic acid standard (heat of combustion 26.454 MJ/kg). The ground material sample (approximately 0.5 g) was compacted into a tablet and burnt in an oxygen bomb calorimeter to determine the calorific value. A cotton thread was attached to the platinum ignition wire and placed in contact with the tablet. The HHV, based on the oven-dry weight of the sample, was calculated as follows (CEN/TS 14918 (2005)),

$$HHV_d = HHV_w \times \frac{100}{(100 - MC)} \tag{1}$$

where HHV_d is the higher heating value at constant volume of the dry (moisture-free) fuel, HHV_w is the higher heating value at constant volume of the fuel as received, and MC is moisture content of the sample (as percentage by mass on an air-dried basis).

Data Analysis

Analyses of variance (ANOVA) using SAS/STAT software version 9.2 (SAS Institute Inc., NC, USA) of the SAS system were performed. Differences between individual levels were compared through Tukey's multiple comparison tests at a 5% probability level.

RESULTS AND DISCUSSION

Chemical Composition

The chemical composition of sugar maple and yellow birch wood is presented in Table 2. Ash content is an important parameter to monitor since it can cause problems in the combustion and conversion processes (Obernberger and Thek 2010; Meincken and Tyhoda 2014). In the current study, the mean ash content of the sugar maple wood varied from 0.38% in the R vigor class to 0.73% in the S vigor class and 0.97% in the M vigor class ($p < 0.0001$). The mean ash content of yellow birch wood varied from 0.27% in the R vigor class to 0.26% in the S vigor class and 0.47% in the M vigor class ($p = 0.0036$). The M class in both sugar maple and yellow birch contained more ash than the other two higher quality classes (S and R). This finding is in agreement with the results obtained by Good *et al.* (1955), who also found that the

amount of ash is higher in stained wood as compared to sound sugar maple sapwood. According to Shigo and Sharon (1970), the increase in mineral content is associated with the processes of discoloration and decay in the sugar maple. Tattar *et al.* (1971) studied changes in wood constituents associated with the discoloration and decay of sugar maple. These authors also found that the amounts of total, insoluble, and soluble ash content increased appreciably in the order of clear tissue, discolored tissue, and decayed tissue. Wood from the less vigorous trees has shown bio-deterioration in the form of sapstain fungi and wood rotting fungi (Fig. 1). Therefore, another explanation for the elevated ash contents in M class wood could be that the original mineral components of wood were not efficiently removed during biodeterioration, which then became concentrated in the remaining material.

The ash contents of the extracted wood samples were also determined. The results shown in Tables 2 and 3 indicated that the ash content of all extracted wood samples was appreciably lower than for the non-extracted wood samples. A larger amount of ash could be removed from the wood samples of the least vigorous trees. Ash removals of 46% and 40% were obtained for the wood samples from the least vigorous sugar maple and yellow birch trees, respectively.

Table 2. Properties of Sugar Maple and Yellow Birch Wood from Different Tree Vigor Class

Properties	Sugar maple			Yellow birch		
	Vigorous tree (R class)	Weakened tree (S class)	Dying tree (M class)	Vigorous tree (R class)	Weakened tree (S class)	Dying tree (M class)
Ash content (%)	0.38[c] (0.03)	0.73[b] (0.07)	0.97[a] (0.05)	0.27[b] (0.03)	0.26[b] (0.02)	0.47[a] (0.05)
Ethanol-toluene extract (%)	3.17[a] (0.22)	2.39[b] (0.24)	3.40[a] (0.40)	1.88[b] (0.35)	2.20[ab] (0.43)	2.87[a] (0.23)
Hot water extract (%)	2.27[b] (0.11)	2.48[b] (0.11)	3.92[a] (0.37)	1.46[b] (0.06)	1.27[c] (0.08)	2.26[a] (0.06)
Total extracts (%)	5.44[b] (0.20)	4.88[c] (0.31)	7.32[a] (0.03)	3.35[b] (0.41)	3.47[b] (0.45)	5.12[a] (0.30)
Klason lignin (%)	21.46[c] (0.33)	22.89[b] (0.76)	23.53[a] (0.83)	18.60[c] (0.18)	20.18[b] (0.72)	21.51[a] (0.94)
Acid soluble lignin (%)	3.59[a] (0.49)	3.53[a] (0.40)	3.29[a] (0.08)	4.59[a] (0.24)	4.06[a] (0.20)	4.15[a] (0.34)
Total lignin (%)	25.06[c] (0.35)	26.40[b] (0.52)	26.83[a] (0.75)	23.20[b] (0.45)	24.23[ab] (0.92)	25.70[a] (1.30)
HHV (MJ/kg)	19.59[a] (0.08)	19.68[a] (0.10)	19.62[a] (0.12)	19.57[b] (0.06)	19.65[ab] (0.11)	19.82[a] (0.14)

Standard deviations are in parentheses. All values are based on the oven-dry weight of the original (non-extracted) sample. For each property of a tree species, the comparison is based on means. Values with different letters (a, b, c) indicate significant differences at the $\alpha = 0.05$ level.

The ash contents of fuels should be as low as possible since ashes in biomasses have a number of negative impacts on the combustion process. Low ash content in wood fuels could benefit the end users in terms of energy content and time for emptying ash (van Loo and Koppejen 2008). As reported by Alakangas *et al.* (2006), a raw

material ash content of less than 0.7% is a requirement for the production of high quality solid biofuels (*e.g*., wood briquettes and wood pellets). From these fuel requirements, the primary limitation for the use of low quality trees as raw materials for the production of solid biofuels is the higher ash content levels as compared to healthy trees. However, the present results showed that extraction can reduce the ash content significantly. In addition, hot water extraction could increase the dimensional stability and compressibility of woody materials (Paredes *et al.* 2008; Pelaez-Samaniego *et al.* 2014). Therefore, the results suggested that hot water extraction should be applied to the wood from low vigor trees in order to produce a superior solid biofuel by the removal of undesirable inorganic substances with water prior to the wood's pelletization.

The extractive content is an important parameter that directly affects the heating value (Kataki and Konwer 2001). A high extractive content makes a lignocellulosic material more desirable as a fuel since the extractives increase the heating value of the material (Demirbas 2002; Telmo and Lousada 2011). In the current study, the mean extractives content was 5.44%, 4.88%, and 7.32% for wood samples from sugar maple trees of class R, S, and M ($p < 0.0001$), respectively. The mean extractive content was 3.35%, 3.47%, and 5.12% for wood samples from yellow birch trees of class R, S, and M ($p = 0.0027$), respectively. Wood from the M class trees for sugar maple and yellow birch contained more extractives than wood from the R class trees. This finding is in agreement with the studies of Pearce and Woodward (1986) and Pearce (1991), who reported higher amounts of extractives in the reaction zones of the wood around wounds than in healthy sapwood, and around infections caused by wood-decay fungi. Similarly, St-Pierre *et al.* (2013) found a higher amount of extractives in wood from low vigor yellow birch trees than from fungi infected trees. In addition, Barnett and Jeronimidis (2003) have shown that the occurrence of physical wounds, mechanical stresses, or attacks by biotic organisms induced the production of traumatic tissues in many trees, which involved the accumulation of protecting compounds in the affected areas. Most of these compounds were extractives and appeared in higher concentrations in the corresponding wood.

The ANOVA indicated that there were significant effects of tree vigor classes on the lignin content of sugar maple ($p < 0.03$) and yellow birch ($p < 0.05$) trees. The total and Klason lignin contents in the sugar maple ranged from 25.06% and 21.46%, respectively, in wood from the R class trees, to 26.40% and 22.89% in the S class, and to 26.83% and 23.53% in the M class trees. A similar pattern was observed for yellow birch, in which total and Klason lignin contents increased significantly from 23.20% and 18.60%, respectively, in the wood from the R class trees, to 24.23% and 20.18% in the S class trees, and to 25.70% and 21.51% in the M class trees. A possible explanation for the appreciable increase in lignin content is that the lignin actually increases during the discoloration and decay processes due to its resistance to degradation by pathogens (Craft and Audia 1962; Hawkin and Boudet 2003). Jane *et al.* (1970) also mentioned that some wood rotting fungi, termed 'brown rot', break down the cellulose and the related materials and leave a brown residue that consists mostly of lignin. Therefore, the higher lignin contents obtained in this work could be due to the loss of cellulose and other polysaccharides, leaving behind the discolored lignin residual.

Prior research (Nguyen *et al.* 2015) has shown that wood from low vigor trees was more suitable for making wood pellets due to a lower friction in the pelletizer die and a higher mechanical strength of the pellets. It is known that wood extractives could act as lubricant in the pellets die and lignin could act as adhesive between the wood particles (Kaliyan and Morey 2009). Therefore, the higher extractive content and the higher lignin content found in wood from low vigor trees in the current study could explain the lower friction in the pellets die and the higher mechanical strength of pellets made from this material as reported by Nguyen e*t al.* (2015).

Calorific Value

The calorific values of sugar maple and yellow birch are presented in Tables 2 and 3. The results showed that variations in the HHV between the tree vigor classes and the wood species were very small, ranging from 19.57 to 19.82 MJ/kg for the non-extracted wood samples and from 19.28 to 19.64 MJ/kg for the extracted wood samples. The ANOVA indicated that there were no significant effects of tree vigor classes on the HHV of non-extracted wood samples from sugar maple ($p = 0.55$) and yellow birch trees ($p = 0.07$). Only a small increase in the HHV of extracted wood samples was recorded in the M class of yellow birch ($p = 0.03$). This finding could be explained by the variations in amounts of extractives, lignin and ash among the tree vigor classes. The higher amounts of extractive and lignin contents in wood from the low vigor trees had a positive impact on the calorific values even when considering the negative effect of their higher ash content on this property.

Table 3. Properties of Extracted Sugar Maple and Yellow Birch Wood

Properties	Sugar maple			Yellow birch		
	Vigorous tree (R class)	Weakened tree (S class)	Dying tree (M class)	Vigorous tree (R class)	Weakened tree (S class)	Dying tree (M class)
Ash* (%)	0.29c (0.06)	0.41b (0.03)	0.52a (0.02)	0.17b (0.02)	0.19b (0.01)	0.28a (0.05)
Total lignin* (%)	26.46b (0.35)	27.76ab (0.64)	28.93a (0.85)	24.00b (0.55)	25.16ab (1.04)	27.06a (1.41)
HHV* (MJ/kg)	19.57a (0.07)	19.64a (0.07)	19.56a (0.05)	19.28b (0.01)	19.41ab (0.07)	19.51a (0.11)
Mass yield† (%)	94.55b (0.20)	95.12a (0.31)	92.67c (0.03)	96.65a (0.11)	96.52a (0.45)	94.87b (0.30)
Energy yield‡ (%)	94.45a (0.31)	94.93a (0.52)	92.39b (0.67)	95.21a (0.35)	95.31a (0.94)	93.36b (0.57)

Standard deviations are in parentheses. All values are based on the oven-dry weight of extracted sample. For each property of a tree species, the comparison is based on means. Values with different letters (a, b, c) indicate significant differences at the α = 0.05 level. Note: * determined after wood samples were extracted sequentially with ethanol-toluene mixture and hot water in accordance with ASTM D1107-96 and ASTM D1110-84 standards, respectively; † obtained by dividing the weight of extracted solid fraction by weight of its original (non-extracted) sample; and ‡ obtained by multiplying the mass yield by HHV of the extracted sample and dividing by HHV of the original (non-extracted) sample.

The results of the present study also indicated that the removal of extractives did not alter the HHV of sugar maple wood, while the removal of extractives showed a small reduction in the HHV of yellow birch wood. These findings are supported by

the results reported by Rossi *et al.* (2013), in which the removal of extractives did not affect, led to a decrease, and caused an increase of the HHV in jatoba (*Hymenaea courbaril*), cedro arana (*Cedrelinga catenaeformis*), and ipe (*Tabebuia* spp.) woods, respectively. These authors suggested that the HHV of wood after extractives removal depends on their chemical composition. Also, this finding may be explained by the nature of the components and the relative quantities present in the fuel. Some extractives contain terpenoid hydrocarbons and lipids, while others contain phenolic compounds with higher oxygen contents than the former compounds. Since combustion of an organic compound is related to its chemical composition, organic compounds containing only carbon and hydrogen produce more heat energy when burned than those containing also oxygen (Senelwa and Sims 1999; Moya and Tenorio 2013).

One can observe from Table 3 that the extraction had a negligible effect upon the HHV of sugar maple and yellow birch, this effect being somewhat more significant ($p = 0.0003$) in the case of yellow birch wood which contains triterpene extractives rich in carbon, which are extracted with ethanol (St-Pierre *et al.* 2013). While HHV represents the absolute value of the specific energy of combustion per unit mass of a solid biofuel, energy yield represents the percentage of energy conserved in the solid fraction following the extraction process. It is an important parameter for the evaluation of the biofuel conversion process. Results indicated that energy yield following the extraction of sugar maple and yellow birch wood ranged between 92.39 and 95.31% (Table 3). It corresponds to about 5 to 8% of energy loss through the extraction. The energy yield calculated for wood sample of the least vigorous (M vigor class) trees is significantly lower than that of the most vigorous (R vigor class) trees for both sugar maple ($p = 0.0024$) and yellow birch ($p = 0.02$). This could be explained by the greater amounts of extractives removed from wood of the least vigorous trees through the extraction. Because of the high value by-products obtained through the extraction process, the higher amounts of extractives in the wood of less vigorous trees could compensate for the energy loss in the solid fraction through the extraction.

CONCLUSIONS

1. Tree vigor for sugar maple and yellow birch had significant effects on the chemical composition of the wood, which included extractives, ash, and lignin content. The less vigorous trees had higher wood extractives, ash, and lignin content than healthy trees.

2. There were no significant differences in the higher heating value of wood between tree vigor classes and between the non-extracted and the extracted wood samples. This can be considered as a value-added advantage because the greater amounts of high-value extractives in the less vigorous trees could be a supplementary benefit that compensates for the energy loss in the solid fraction through the extraction.

3. The higher extractive content and higher lignin content of wood from less vigorous trees found in this study support prior research which suggested that

wood particles from less vigorous trees were more suitable than those from vigorous trees to make wood pellets.

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