ASSESSMENT OF FUEL QUALITY CHANGES DURING STORAGE OF BIOFIBRE AND ITS EFFECT ON COST

by

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ABSTRACT

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Keywords: bioenergy, northwestern Ontario, moisture content, thermal value, ash content, grinding, biomass, cost, energy analysis, input output ratio.

Bioenergy, energy produced from renewable biomass, can potentially replace fossil fuels and create employment in northwestern Ontario. However, the procurement of biomass for energy production can be uneconomical due to high moisture content, low thermal value and low energy density. Studies in Europe have shown that biomass can be stored in the field to improve the fuel quality. Logging residues stored in various forms was investigated to gain an understanding of the effect of storage method and duration on the fuel quality. The fuel qualities assessed were moisture content (MC), thermal value and ash content. Also a case study is presented with information on cost of processing and transporting salvaged wildfire burnt biomass, and the net energy balance of the entire operation.

The MC was reduced from a green state to 27%, 21.6% and 22.2% (green weight basis) after 1, 2 and 3 year of storage in roadside slash piles, respectively. In cut-to-length blocks, the MC was reduced from a green state to 30.1%, 24.0% and 25.5% after 1, 2 and 3 years of storage, respectively. Windrows displayed lower MC values than beehives and softwoods generally displayed lower MC values than hardwoods with few exceptions. The thermal values ranged from 19.5 to 23.1 $MJ \cdot kg^{-1}$ for all species, tree components and storage years. Storage years had no significant effect on the thermal value, but diameter and species did. Generally, smaller diameter stems displayed higher thermal value than larger diameter stems and softwoods contained higher values than hardwoods. The ash content ranged from 0.4% to 8.4% for all species, components and storage years. Diameter produced significantly different values in logging residues of both cut-to-length blocks and roadside slash piles; smaller diameter stems showed higher ash content. In cut-to-length blocks, the ash content was reduced significantly with an increase in storage years.

The cost of felling, extracting, processing and transporting biomass using the full-tree to roadside, roadside crusher to mill (FT-CR) system was estimated at $\$29.65 \cdot gt^{-1}$. Biomass from the 35-year-old burnt stand was transported to a mill 15 km (roundtrip) away. The energy input to output for harvesting and roundtrip transportation was estimated at 1:60. The study demonstrates that a significant reduction in cost can be achieved through drying biomass in the field; post drying, there is less transport of water and also the thermal output of the delivered feedstock is higher, leading to a reduction in the overall cost.

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CHAPTER 1 INTRODUCTION

Bioenergy, energy produced from renewable biomass, has received much attention in northern Ontario recently (Kryzanowski 2009). It has the potential to become part of the solution to the forest industry crisis in the region whilst mitigating climate change (Morris 2006). Mill closures have been a regular event in northern Ontario despite the fact that each closure is economically devastating to the region (Albert 2007). The industry's loss of competitiveness can be attributed to global and domestic pressures. The forest sector is energy intensive; it traditionally relied on low cost electricity but now faces the challenge to stay competitive with much higher electricity cost (Frédéric 2005). The Minister's Council on Forest Sector Competitiveness- Final Report estimated that Ontario's industry faces the highest electricity cost in all of United States and Canada (MCOF 2005).

On the global front, Canada is a signatory to the Kyoto protocol; however the percentages of emissions are up from the 1990 levels (Bradley 2009). Electricity generation through fossil fuels leads to a significant increase in atmospheric carbon dioxide concentrations (IPCC 2007). Coal and natural gas contribute approximately 42% to Ontario's existing generation capacity (IESO 2009). The Government of Ontario has pledged to phase out coal fired generating stations by 2014 mainly to reduce green house gases emissions (Tang 2009). In support of the goal, the government introduced the biofibre policy in August 2008 to promote the utilization of logging residue and unmerchantable biomass (Koivisto 2008). The policy allows for the allocation of biofibre for the production of energy and other value-added bioproducts. The policy defines biofibre as, "tree tops, cull trees or portion of trees, individual and stands of unmerchantable and unmarketable trees, and trees salvaged after being damaged by fire, wind or other types of damage". Replacement of fossil fuels with biomass, a carbon neutral feedstock, creates employment and regional economic gains (Domac *et al.* 2005)

Despite the policy in place for the utilization of forest biofibre, the information on the cost and quality of the regional feedstock is deficient. Such information is key to writing successful business plans and consequently creating jobs in the region. The oil crisises of the 1970's and early 1980's had stimulated public interest to replace oil and other fossil fuels with renewable feedstock (Islam *et al.* 2004). The Canadian government started several initiatives to catalyze the utilization of renewable energy at a commercial level. The most relevant to the forest sector was the federal interdepartmental initiative, Energy from the Forest (ENFOR) program, established in 1978 and administered by the Canadian Forestry Service (CFS) with an objective to generate knowledge and technology on bioenergy production through research and development. Although the program produced a number of reports, the public interest on renewable energy faded due to a decrease in oil price and expanding availability of natural gas (Islam *et al.* 2004). As a result there were no governmental policies developed to guide ENFOR to the implementation phase. The feasibility of generating electricity through burning biomass is dependent on the cost and quality of biofibre (Forrester 2004; Rentizelas *et al.* 2008). The general objective of the thesis is to gain an understanding on the quality changes of biofibre during storage and get an insight on costs entailed in processing and transporting of biofibre in the northwestern region of Ontario. Logging residue stored in various forms was investigated to gain an understanding on the effect of storage method and duration on the fuel quality. Also a case study is presented with information on cost of processing and transport of salvage wildfire burnt biomass, and the net energy balance of the entire operation.

1.1. BACKGROUND INFORMATION

Biofibre includes tree tops, cull trees or portion of trees, individual and stands of unmerchantable and unmarketable trees, and trees salvaged after being damaged by fire, wind or other types of damage (Bradley 2007). The focus of this thesis is on two biofibre sources: salvage biomass from wildfire burnt areas, and logging residue remaining after merchantable timber harvest. Fire is a frequent and natural occurrence in the boreal forest. On average, over 10,000 ha of forest area or over 1 million m^3 of wood that is part of the harvest schedule is consumed by wildfire every year in Ontario (OMNR 2008).

Biofibre delivery system consists of harvesting, storage, processing and transportation (Hall *et al.* 2001). Feasibility of the system depends on the biofibre quality and cost incurred during procurement. Therefore, accurate information on both quality and cost is important for development of a reliable production system. Harvesting method refers to the form in which wood is delivered to the logging access road (Pulkki 2003). Harvesting system refers to the tools, equipment and machines used within the harvesting method. The harvesting methods most common to northern Ontario is the full tree method followed by cut-to-length method. In 2005, approximately 48% of the harvest operations in eastern Canada were with the full tree method, with cut-to-length representing 40% (FERIC 2008).

In the full tree harvest method (FT), trees are felled and brought to roadside with the tree intact where they are processed to the specifications of the mill as either logs or tree-lengths (Pulkki 1997). The harvesting systems employed during full tree harvesting include:

- Feller buncher/grapple-skidder/delimber-debarker-chipper system (FT-CH)
- Feller buncher/grapple-skidder/stroke-delimber/slasher harvesting system (FT-SW)
- Feller buncher/grapple-skidder/stroke-delimber harvesting system (FT-TL)

The FT method produces logging residue that is concentrated mainly in windrows along the roadside as the removal of tops and limbs is done at the roadside (Pulkki 1997; Pulkki 2003). As such, there is a lesser amount of logging residue scattered throughout the cutover which mainly consists of residual and broken stems, and felled trees missed by the grapple skidder (Ride 1998). The roadside slash has typically been piled and burnt in the fall (Luke *et al.* 1993). The objective of burning is to recover land for regeneration and reduction of wildfire hazard.

With the cut-to-length harvesting method (CTL) trees are felled, delimbed and bucked to various assortments at the felling location; meaning the tops, limbs and stem outside the merchantable specifications are left on the cutover (Pulkki 1997; Ride 1998). The cut-to-length method is generally employed through the single-grip harvester/forwarder system. Although the cut-to-length method is currently used in northern Ontario to a lesser extent, it is on the rise due to its versatility and lower environmental impact. Since trees are processed in the cutover, logging residue is left throughout the cutover in windrows, small heaps or scattered.

The components of trees leftover in the forest after extraction of merchantable stems is referred to as logging residue (LR). The merchantable stem of a tree, as illustrated in Figure 1, is generally directed toward manufacturing of higher value products; the crown and branches are left on site as logging residue. The maximum stump height allowed according to the Ministry of Natural Resources Scaling Manual (OMNR 2007) is 30 cm. The stump height can be increased up to 60 cm if the butt diameter is greater than its height.

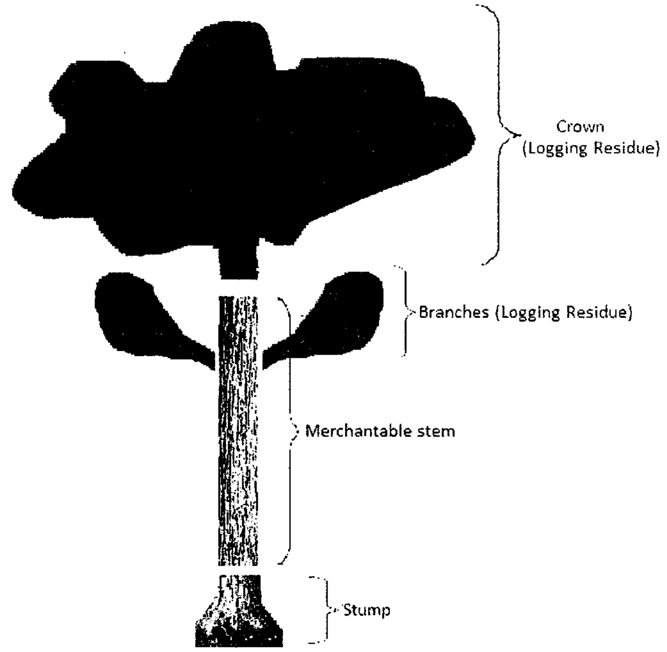


Figure 1. Components of tree left behind as logging residue.

The quantity of logging residue left in the forest depends on the final destined product of the timber. The major products manufactured in northern Ontario are oriented strand board (OSB), veneer, lumber, and pulp and paper (CFS 2005). The log specification for OSB range from 10 cm minimum to 63 cm maximum diameter; veneer logs have an even narrower specification at 22 cm minimum and 62 cm maximum diameter. There is a variable range for maximum acceptable diameter accepted for sawlogs but the minimum diameter accepted is generally 9 cm. With regards to pulpwood, a minimum top end diameter of 5 cm is acceptable.

Anything above and below these specifications are left in the forest. Defective logs also contribute a certain amount towards logging residue; stump rot, heart check, shake, seams, forks, butt flare, sweep, crooks, splits and worm holes are some of the defects that produce additional logging residue (OMNR 2007).

The quality of logging residue left in the forest is subject to seasonal variation; storage method and duration also affects the quality (Rogers 1981; Gigler *et al.* 2004). Low moisture content, high heat value and low ash content translate to high fuel quality (Nurmi 1999; Jirjis 2005; Petterson and Nordjfell 2007). Studies in Europe have demonstrated that certain storage regimes can enhance the quality of biomass feedstock while others will deteriorate the quality.

Following storage, transport of forest residues from the forest to an energy plant is a key activity in the bioenergy supply chain (Allen *et al.* 1998; Hall *et al.* 2001). There are a range of potential combinations of systems to process and transport the biomass (FERIC 2008). One such system, full-tree to roadside, roadside crusher to mill (FT-CR) system, is used to fell and bunch the biomass, skid it to roadside as full trees, crush it at roadside and transport it on a chip truck to the power generating station.

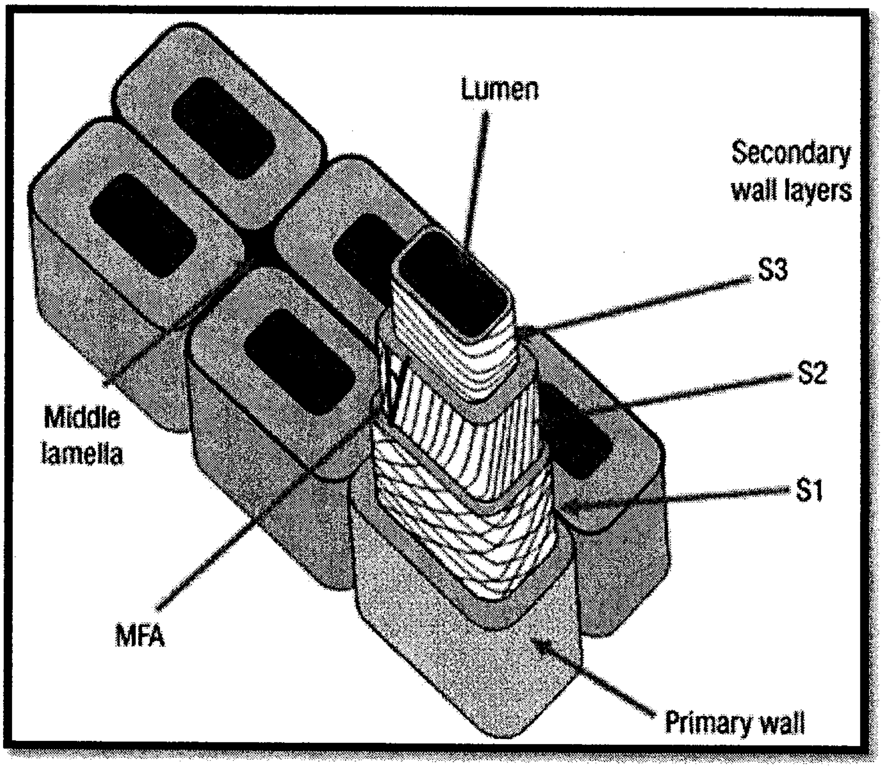
1.2. THESIS OUTLINE

The thesis is divided into four chapters. Literature review on wood morphology, fuel quality changes during storage, and cost of communition and transport is presented in the remainder of chapter 1. Findings from the study on the effect of storage method and duration on the fuel quality are presented in chapter 2. A case study is presented in chapter 3 with information on cost of processing and transport of biomass, and the net energy balance of the entire operation. Chapter 4 summarizes the findings of the entire thesis, outlines limitations and recommendations for future studies.

1.3. LITERATURE REVIEW

1.3.1. Wood Cell

The principle building block of wood is xylem cells produced by cell division in the vascular cambium and are aligned parallel to the trunk or branch (Winandy 1994). Each individual cell has four distinct cell wall layers (Figure 2). Each layer is composed of a combination of three chemical polymers: cellulose, hemicelluloses and lignin (Bowyer *et al.* 2002). Table 1 shows the proportion of the polymers on a few different types of biomass. The cellulose microfibrils are encrusted by hemicelluloses and lignin to achieve a fibre reinforced structure. The microfibrils are highly ordered bundles of cellulose chains that give strength and stiffness to the cell wall.



Source: Kretschmann (2003)

Figure 2. The anatomy of wood cells.

Cellulose is the chief component of the cell wall (Raven *et al.* 1999). It is an insoluble complex carbohydrate formed of micro fibrils of glucose molecules attached end to end. Each glucose unit contains three hydroxyl groups which can form hydrogen bonds with water in amorphous regions (Siau 1995).

Hemicellulose is a polysaccharide resembling cellulose but is more soluble and less ordered (Raven *et al.* 1999). Cellulose is crystalline, strong and resistant to hydrolysis, whereas hemicellulose has a random, amorphous structure with little strength.

Lignin, another constituent of the cell wall, adds compressive strength and stiffness to the cell wall (Raven *et al.* 1999). Lignification, the process of lignin deposition, helps the cell wall to withstand substantial tensile forces, and the compressive forces of gravity (Raven *et al.* 1999). Lignin facilitates upward transport of water in the conducting cells of the xylem by limiting the outward movement of water from the cells. In addition, lignin assists the water-conducting cells in resisting the tension generated by the stream of water. Lignin deposition also protects the plant from fungal attack by increasing the resistance of walls to mechanical penetration (Panshin and Zeeuw 1980; Raven *et al.* 1999). The proportion of lignin in biomass along with the carbon content and the thermal value is displayed in Table 1.

Table 1. Biomass composition and the carbon content and heating value.

Biomass Component	Poplar (% mass)	Pine (% mass)	Carbon Content (% mass)	Heat Value (MJ·kg^{-1})
Cellulose	41	40	40-44	17
Hemicellulose	33	25	40-44	17
Lignin	26	35	63	25
Ash	1	1	0	0

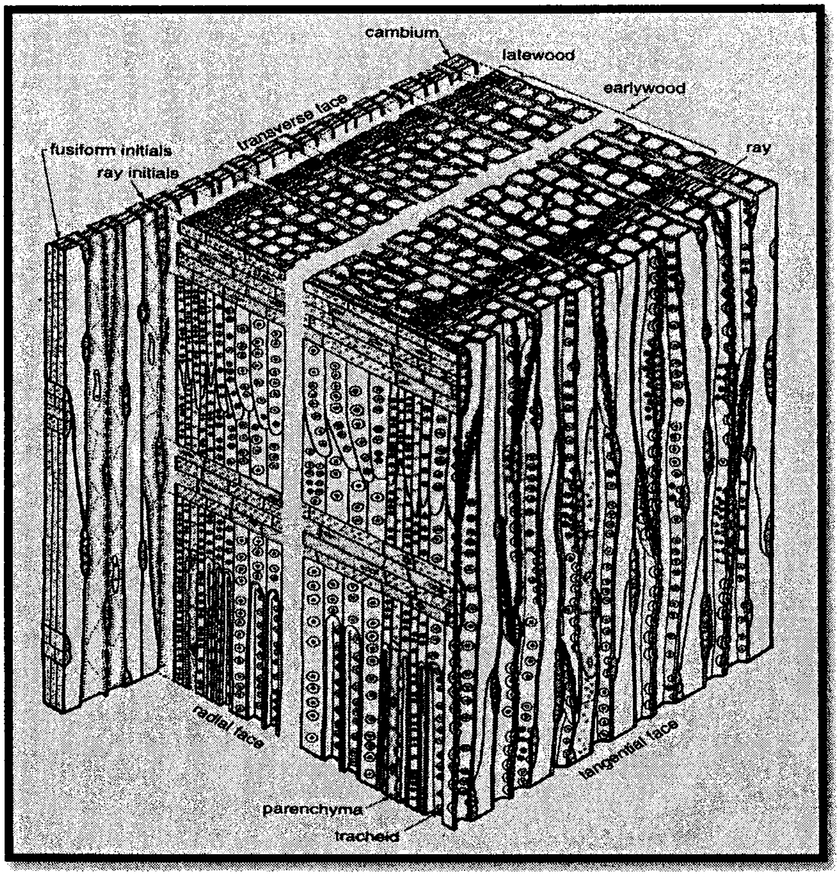
Source: GCEP (2005)

1.3.2. Wood Morphology

1.3.2.1. Softwood/Hardwood

Wood is botanically classified into softwood and hardwood. In this report, species included in each category are those utilized commercially in northern Ontario and include Balsam Fir (*Abies balsamea* (L.) Mill.), White Spruce (*Picea glauca* (Moench) A. Voss), Black Spruce (*Picea mariana* (Mill.) BSP.), Jack Pine (*Pinus banksiana* Lamb.) under the softwood category. Hardwood species include Red Maple (*Acer rubrum* L.), Paper Birch (*Betula papyrifera* Marsh.) and Trembling Aspen (*Populus tremuloides* Michx.).

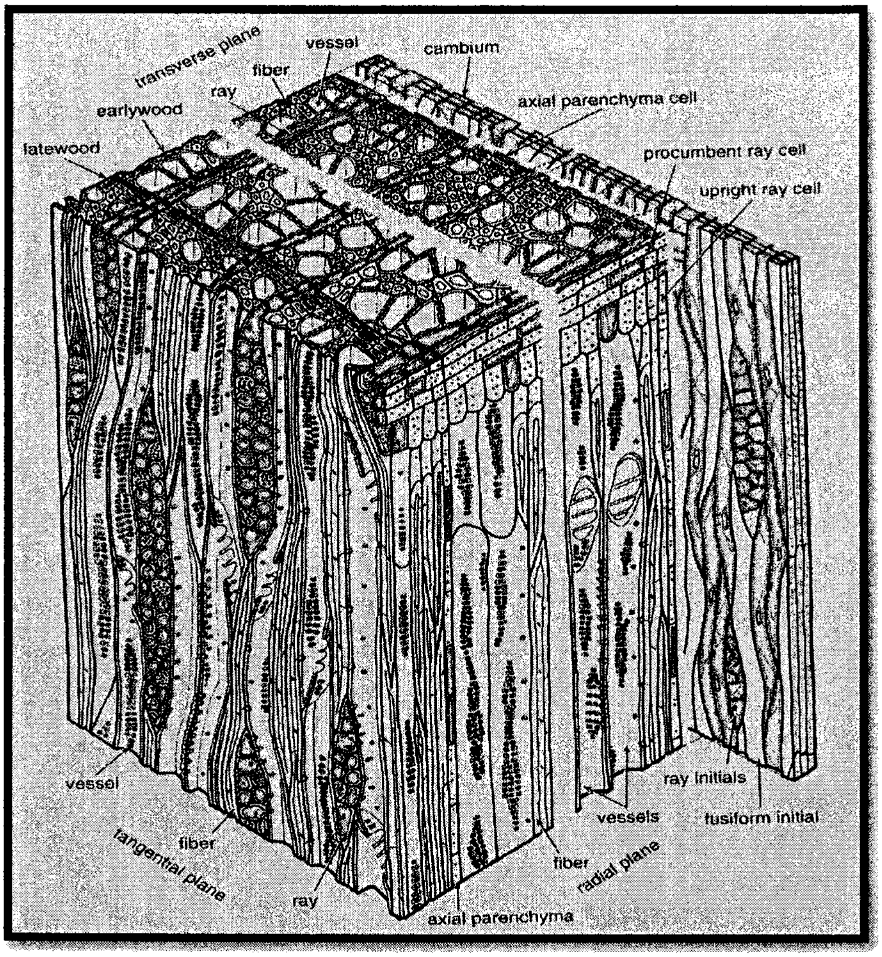
Softwoods have a simple cellular structure with approximately 93% of the cells being longitudinal tracheids, and the remaining 6% and 1% being wood rays and extractives, respectively (Siau 1995). Longitudinal tracheids are cells that give the tree support and conduct water. Pits in the cell walls of the tracheids enable sap to pass from cell to cell as it moves up the stem. Figure 3 is a sketch of a typical softwood structure.



Source: Evert (2006)

Figure 3. Three-dimensional scheme showing structure of softwood xylem.

The cellular structure of hardwoods is more complex and it varies greatly between species (Raven *et al.* 1999). Hardwoods produce two distinct cell types for conduction and strength: vessels for conduction and fibers for strength. The cellular structure of hardwoods consists of libriform fiber, fiber tracheids, vessel elements, longitudinal parenchyma, vasicentric tracheids, vascular tracheids and wood rays; their proportion and presence is variable between species. A sketch of a typical hardwood cellular structure is presented in Figure 4.



Source: Evert (2006)

Figure 4. Three-dimensional scheme showing structure of hardwood xylem.

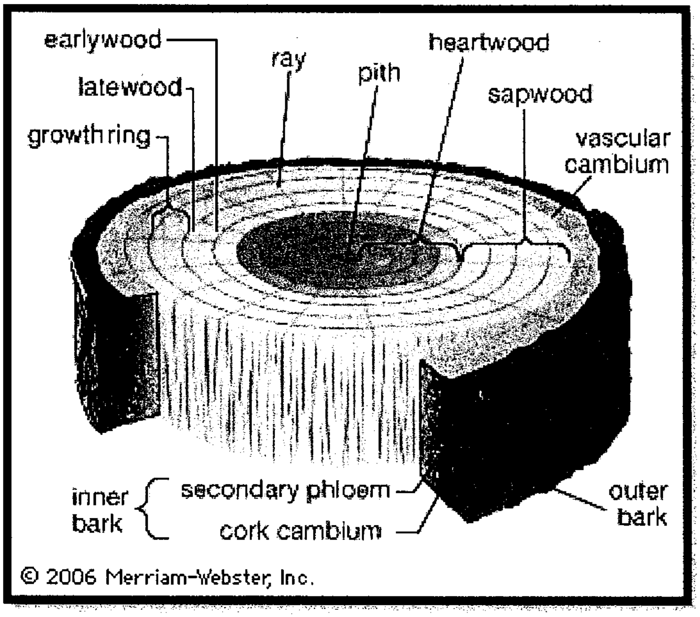
1.3.2.2. Sapwood/Heartwood

All wood in the tree is formed as sapwood (Bowyer *et al.* 2002); the role of sapwood is to conduct water from roots to the leaves. It is the outermost wood found closest to the cambium hence is the youngest wood (Figure 5). As sapwood ages, it is genetically programmed to be converted to heartwood through deposition of chemical substances. Heartwood forms the central support of the tree. The deposition of chemical substances gives heartwood a darker color than sapwood in most species.

Sapwood is generally more permeable than heartwood due to pit aspiration in softwoods and tyloses in hardwoods (Siau 1984).

1.3.2.3. Earlywood/latewood

In temperate regions, earlywood is formed in the spring during the earlier portion of the growing season, and latewood is formed at the end of the growing season (Punches 2004). Earlywood has shorter cells and a lower density, while latewood displays higher density resulting from smaller tracheid/fiber radial diameter and large tangential wall thickness (Larson *et al.* 2001).



Source: Tsoumis (2009)

Figure 5. Cross sectional view of a tree trunk.

1.3.2.4. Reaction wood/Juvenile wood

Reaction wood is formed in wood in response to bending of the main stem and, to maintain branch angle. Reaction wood differs from normal wood chemically, physically and anatomically (Siau 1984). Reaction wood, termed compression wood in softwoods, has only 30% cellulose compared to 42% in a normal wood and a higher proportion (38%) of lignin compared to normal wood (28%). Conversely, tension wood in hardwoods has a much higher cellulose content than normal wood and lower lignin content on a weight basis (Siau 1984; Bowyer *et al.* 2007).

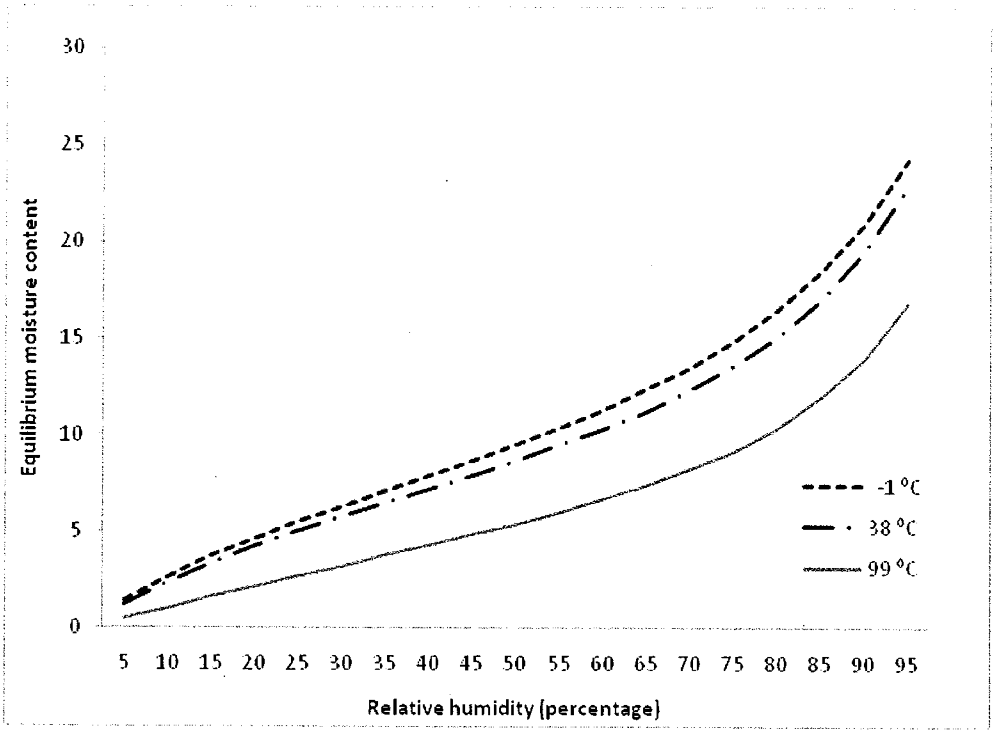
Wood formed in the early stages of stem growth is called juvenile wood (Bowyer *et al.* 2007). There are relatively few latewood cells in the juvenile zone, and a high proportion of earlywood cells displaying thin wall layers. The result is low density and a corresponding low strength in comparison to mature wood. However, the component of trees where the juvenile wood is present is due to the flexibility required in these regions. In conifers of North America, density is typically 10-15% lower in the juvenile core. Juvenile wood also has low cellulose and high lignin content.

1.3.3. Fuel Characteristics

In bioenergy fuel quality assessment, the properties assessed are those that affect the energy yield and transportation costs: i.e., moisture content, heat value and ash content (Pettersson and Nordfjell 2007).

1.3.3.1. Moisture Content

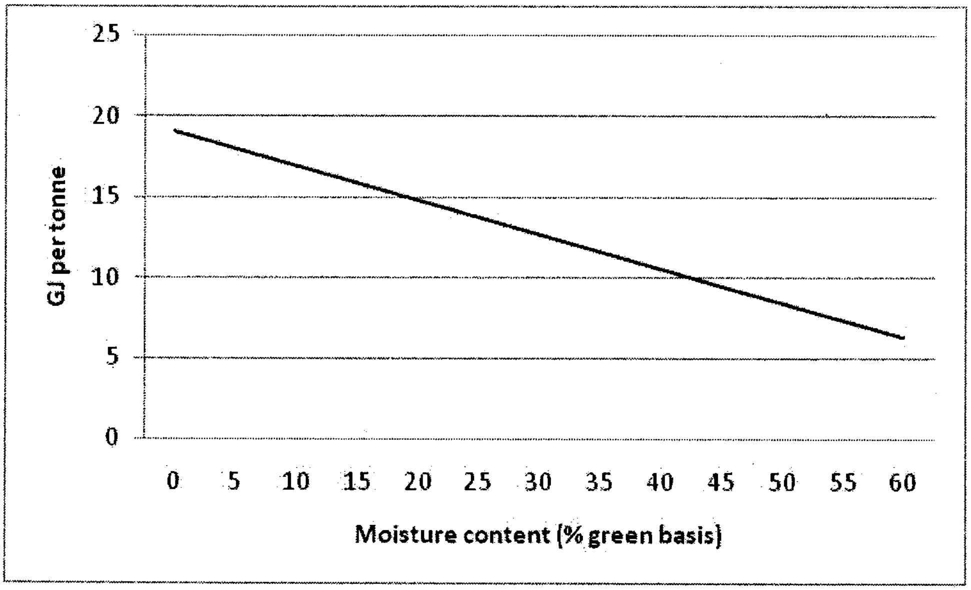
Moisture in wood can be found as either free water or bound water. Water present in the cell lumina, held by capillary forces, is referred to as free water whereas water molecules in the cell walls held by hydrogen bonding is referred to as bound water (Siau 1995). The state at which bound water is present but the cell lumina are emptied of free water is referred to as the fiber saturation point (FSP). The amount of bound water present in wood depends on the relative humidity of the surrounding air (Simard 1968). After a certain period of drying, wood will eventually reach a moisture level that is in equilibrium with its surrounding air; the state is referred to as the equilibrium moisture content (EMC) (Siau 1995). Once it reaches this state, the wood loses bound water as the relative humidity drops, and gains moisture as the relative humidity increases until the balance is restored. The relative humidity of air is dependent on the temperature since it is the temperature that governs the capacity of air to hold moisture; Figure 6Figure **6** shows the general relationship between EMC, relative humidity and temperature.



Source: Simpson (1999)

Figure 6. Equilibrium moisture content as a function of temperature and relative humidity.

There are three specific advantages to drying wood for the production of bioenergy: 1) drying wood renders it less susceptible to decay as fungal activities generally require a MC higher than FSP; 2) dried logging residue is much lighter per volume hence transportation costs are reduced (Hakkila 1989; Petterson and Nordjfell 2007); and 3) the net thermal value from logging residue is dependent on the moisture content of the feedstock as shown in Figure 7.



Source: EECA (2007)

Figure 7. General relationship between heat value and moisture content of wood.

In the literature, MC is expressed in both wet basis and oven dry basis (Bowyer *et al.* 2002). Wet basis, also known as green basis, is the ratio of the weight of water in the wood to the green wood weight. Whereas, MC dry basis is the ratio of weight of water in the wood to the oven dry weight of the wood. The formulae for calculating moisture content on green basis is shown by equation (1).

$$\text{MC(green basis)} = \frac{\text{Green wood weight} - \text{Oven dry weight}}{\text{Green wood weight}} \text{X } 100 \qquad [1]$$

Nurmi (1999) conducted a study in Finland on Norway spruce LR piled 4.5 m high. It was found that the average MC was reduced from 56%, green weight basis (GW), to approximately 40% (GW) after being piled from September 1994 to September 1995. Another treatment of the same study involved leaving the residue on the cutover from September 1994 to June 1995, and then forwarding it to a landing where it was piled until September 1995. This treatment resulted in a lower MC of 28% (GW). When LR created from winter harvest is left on the site, the MC decreases from 55-60% to 25-30% (GW) during summer and rises to 45-50% (GW) by autumn (Hakkila 1989). In comparison, 4-5m piles resulted in MC of 40-45% (GW) during summer and autumn. A similar result was observed by Jirjis *et al.* (1989) in Sweden where small piles of softwood LR were observed during summer. The piles lost MC rapidly only to remoisten during wet weather except in piles that were covered with water repelling paper. Results showed that covered piles had 10% (GW) less MC than uncovered piles. Another study investigated by Petterson and Nordjfell (2007) reported that covered piles had 13% (GW) less MC than uncovered piles.

1.3.3.2. Thermal Value

The photosynthetic energy stored in biomass can be extracted in various ways to be used as energy (Hakkila 1989). Combustion of biomass, or oxidation, is the most widely used method of extracting energy from biomass. The thermal value of a fuel is a measure of the maximum amount of energy that is released on burning a given quantity of the fuel (Kryla 1984). The thermal value released by a fuel depends on the chemical composition of the substance. The major combustible elements in biomass are carbon and hydrogen (Hakkila 1989). During combustion oxygen combines with carbon, producing carbon dioxide, and with hydrogen, producing water as shown by equations (2) and (3).

$$C + O_2 \rightarrow CO_2 + 32.8\ MJ \cdot kg^{-1}\ \text{of}\ C \qquad [2]$$

$$2H_2 + O_2 \rightarrow 2H_2O + 142.2\ \mathrm{MJ \cdot kg^{-1}}\ \text{of}\ H_2 \qquad [3]$$

A high carbon and hydrogen content translates to high thermal values, whereas oxygen, nitrogen, and inorganic elements have the opposite effect (Hakkila 1989). Softwoods on average contain 50.7% carbon and 6.2% hydrogen, and hardwoods contain 49 % carbon and 6 % hydrogen. In the literature thermal value of a fuel is presented in terms of its higher heating value (Kryla 1984). Higher heating value is the gross energy released through combustion, and it includes latent heat contained in the water vapour (McKendry 2002). Lower heating value represents net energy recovered from combustion, and the value varies depending on the conversion technology. Table 2 presents thermal values of various components of 10 boreal tree species from Manitoba, Canada.

Table 2. Oven dry thermal values ($\mathrm{MJ \cdot kg^{-1}}$) of 10 boreal species from Manitoba.

	Species	Stump	Stem	Treetop	Bark	Foliage	Branches	Mean
Softwoods	White spruce	19.8	19.0	21.6	19.8	20.6	21.1	20.3
	Black spruce	19.2	18.8	21.6	19.5	20.9	20.7	20.1
	Jack pine	20.0	19.4	21.2	21.3	21.4	21.3	20.8
	Eastern white cedar	19.4	20.0	19.5	18.7	21.4	18.7	19.6
	Tamarack	19.9	18.8	21.3	19.5	20.1	21.4	20.2
	Balsam fir	19.7	18.7	21.4	18.5	21.5	20.6	20.1
Hardwoods	Aspen	18.7	18.7	20.2	19.5	18.8	19.9	19.3
	Balsam poplar	18.5	17.7	20.5	19.5	17.7	19.1	18.8
	White birch	18.9	18.5	19.8	20.2	21.1	19.7	19.7

Source: Singh and Kostecky (1989)

The variation in the thermal value between tree species and components is due to the difference in the chemical composition. Lignin, resin, terpenes and waxes have higher thermal values than cellulose and hemicelluloses (Hakkila 1989; Demirbaş 2001).

On a weight basis, the thermal value of softwoods is higher than that of hardwoods. Kryla (1984) found the overall mean thermal value of softwoods native to Canada is 21.18 MJ·kg^{-1} while the corresponding hardwood value is 19.35 MJ·kg^{-1}. Singh and Kostecky (1986) reported values of 20.18 and 19.15 MJ·kg^{-1} for softwood and hardwood; respectively, boreal species from Manitoba, Canada. The higher thermal values in softwoods can be attributed to their higher content of lignin, resins, terpenes and waxes (Hakkila 1989).

In conifers, the heat values are higher in foliage and branches than in stem wood (Kryla 1984). Harris (1984) and Koch (1985) found slightly lower heat values in hardwood branches compared to stems. Hakkila (1989) attributes this to the lower lignin content in the branches of hardwoods. Similarly, Arola and Sturos (1980) report a lower heat value for bark in hardwoods compared to the wood and conversely higher heat value for bark of softwoods compared to the wood. On the contrary, Singh and Kostecky (1989) report higher heat values for bark in aspen, balsam poplar and white birch compared to stem wood.

On a volume basis, hardwoods produce much higher heat values due to denser wood (Kryla 1984). In essence, specific gravity of wood is an important characteristic as it determines the net energy potential from a volume of biofibre (Tomsons *et al.* 2003). Table 3 displays the specific gravity of some species found in northern Ontario.

Table 3. Specific gravity values of certain tree species found in northern Ontario

Species	Specific Gravity (12% MC)	Source
Trembling Aspen	0.41	Porter (1981)
Paper Birch	0.51	FORINTEK (2009)
Red Maple	0.54	Bowyer et al. (2002)
Balsam Fir	0.35	Porter (1981)
Red Pine	0.4	Porter (1981)
Jack Pine	0.44	Porter (1981)
Black Spruce	0.43	Porter (1981)
White Spruce	0.37	Porter (1981)

Although the thermal value of logging residue changes during storage, Hakkila (1989) mentions that the change is insignificant. Nurmi and Hillebrand (2007) studied the significance of storage on heating value of Scots pine (*Pinus sylvestris* L.) and downy birch (*Betula pubescens* Ehrh.). The materials stored for varying durations showed no significant difference in the heat value before and after storage. In another study by Jirjis (2005), the effect of storage on fuel quality of willow (*Salix viminalis* L.) chips and chunk wood was studied. Chunk wood showed insignificant difference in the heat value after storage while chips showed slightly larger reductions.

However, the effect of storage on the thermal value is indirect; storage affects MC which consequently affects the net heat value (Rogers 1981; Tomsons *et al.* 2003). Therefore, information on thermal value alone is not sufficient; the accompanying MC is required, as moisture reduces the thermal value proportionally as shown in Figure 7.

1.3.3.3. Ash Content

Commercial production of energy through the combustion of biomass produces ash as residue. The ash of logging residue is made up of inorganic minerals, primarily calcium, magnesium, manganese, potassium and silica (Karltun *et al.* 2008). There can be variation in the proportion and overall ash content due to conditions on the growing site, species, size, age and the tree component (Petterson and Nordjfell 2007). For example, foliage and bark have higher ash content than stem and branches, hardwoods have higher ash content than softwoods, and younger trees have higher ash content than mature trees (Hakkila 1989). The overall cost of energy from LR can rise due to extra transport, dumping and handling costs to deal with ash (Hakkila 1989; McKendry 2002). McKendry (2002) mentions energy from fuel is actually reduced proportionately with ash content.

Theoretically leaching of elements and shedding of needles during storage should reduce ash content (Hakkila 1989; Petterson and Nordjfell 2007). The results obtained by Nurmi (1999) supported the above theory; Norway spruce LR stored in a clearcut from September 1994 to June 1995 and then forwarded to the landing and measured in September 1995 had a reduction in needle mass from 27.7% to 6.9% on a dry basis. When LR was stored on a landing piled 4.5 m high from September 1994 to September 1995, the corresponding reduction was from 27.7% to 18.9% on a dry weight basis.

1.3.4. Communition Equipment and Cost

To minimize the cost of procurement, it is important to research available equipment and operational systems for communition and transport of biofibre (Mitchell 2005). The common comminution methods are chipping, grinding and shredding (Ledrew 2004; Goldstein and Diaz 2005). Chippers cut wood into relatively uniform size and shape wood chips, shredders tear particles apart using rotating shafts mounted with knives which pull wood into pieces between the shafts and the surrounding chamber, and grinders reduce particle size of biomass by repeatedly pounding on it with a hammermill (Goldstein and Diaz 2005).

Desrochers *et al.* (1995) observed two drum type trailer-mounted chippers in New Brunswick and in Maine. In the New Brunswick trial the Erjo 120 HM 903 equipped with a 412 kW Cummins diesel engine was studied. A Nicholson WFP 3A unit with a 450 kW diesel engine was evaluated in the Maine study. The Nicholson WFP 3A was also equipped with a 160 kW diesel engine to drive the chip discharge. The chippers were observed chipping roadside logging residue in cut blocks harvested using the FT method. The production of the Erjo in New Brunswick was 22.2 green tonne (gt) per productive machine hour (PMH) with utilization rate of 83% at a cost of $\$14.32\cdot gt^{-1}$. Meanwhile, the Nicholson in Maine produced 49.2 $gt\cdot PMH^{-1}$ with utilization rate of 60% at a cost of $\$8.24\cdot gt^{-1}$.

Another study by Desrochers (1998) evaluated a 425 horsepower (hp) trailer-mounted Maxigrind 425 grinder near La Sarre, Quebec comminuting roadside logging residue. The machine processed the material (MC 27.5% GW) at a rate of 12 gt·PMH^{-1} with a utilization rate of 68%. The cost attributed to the grinder was $20.63 per oven dry tonne (ODt). The author concludes that the grinder was not an ideal machine for grinding logging residues as the feed hopper was too small.

Asikainen and Pulkkinen (1998) studied the productivity and cost of three machines, Evolution 910R chipper, MOHA chipper truck and Morbark 1200 tub grinder with engine output of 267, 229 and 481 kW, respectively. Logging residues left scattered on the logging site were forwarded to the roadside for communition by the Evolution and Mobark, while the MOHA operated in the logging site. The productivity recorded for each machine were: Evolution was 55 m^3 (loose) per scheduled machine hour (SMH), MOHA processed 23 m^3 (loose)·SMH^{-1}, and Morbark 1200 processed 50-60 m^3 (loose)·SMH^{-1}. The corresponding hourly costs in Canadian Dollars (1998) for Evolution, MOHA and Morbark 1200 were $160, $96 and $134, respectively.

CHAPTER 2 FUEL QUALITY OF LOGGING RESIDUE

2.1. INTRODUCTION

Logging residue is produced year-round, however its immediate transport is costly due to high moisture content at a green state (Pettersson and Nordfjell 2007; Gigler *et al.* 2000). Studies in Europe have shown that logging residue can be stored in the field to improve the fuel quality (Jirjis 2005). The form, duration of storage and the weather conditions affect fuel quality (Pettersson and Nordfjell 2007). There has been no such research done on the fuel quality of logging residues in northwestern Ontario. Knowledge gained in Europe is transferable to northerwestern Ontario to a certain extent, but due to the differences in stored material and weather conditions it is not completely valid.

2.2. STUDY OBJECTIVES

The objective of the study is to determine a storage regime that enhances the quality of logging residue stored in harvest blocks. The desired quality variables assessed are moisture content (MC), thermal value and ash content. It was investigated whether there is a statistical difference in the MC, thermal value and ash content of logging residue stored in various pile configurations for a range of durations.

In slash piles from full tree harvesting operations, it was investigated whether the following variables affect the quality of logging residues:

- Logging residue storage years (1 year, 2 year, 3 year)

- Piles shape (beehive, windrow)
- Pile height (<2 m, >2 m)
- Species (hardwood, conifer)
- Logging residue diameter (small, large)

The shape of the slash piles selected in the study fall either under the general category "half-section of sphere" or "half-ellipsoid" referred to as beehive and windrow, respectively. Logging residue samples with diameter less than or equal to 4 cm is referred to as small, and diameter greater than 4 cm is referred to as large. In cut-to-length harvest blocks it was investigated whether the following variables affect the quality of logging residues:

- Age of logging residue (1 year, 2 year, 3 year)
- Species (hardwood, softwood)
- Logging residue diameter (large, small)

2.3. METHODOLOGY

2.3.1. Study Area

The study materials were located in harvest blocks to the west of Atikokan, Ontario, Canada (Figure 8 and Figure 9). A block is a unit of land allocated for harvest generally under the same logging method in the same annual work schedule (AWS) and also prescribed a regeneration method in its totality. The AWS outlines all forest management activities, including harvesting, that are scheduled for a one year period extending from April 1st to March 31st.

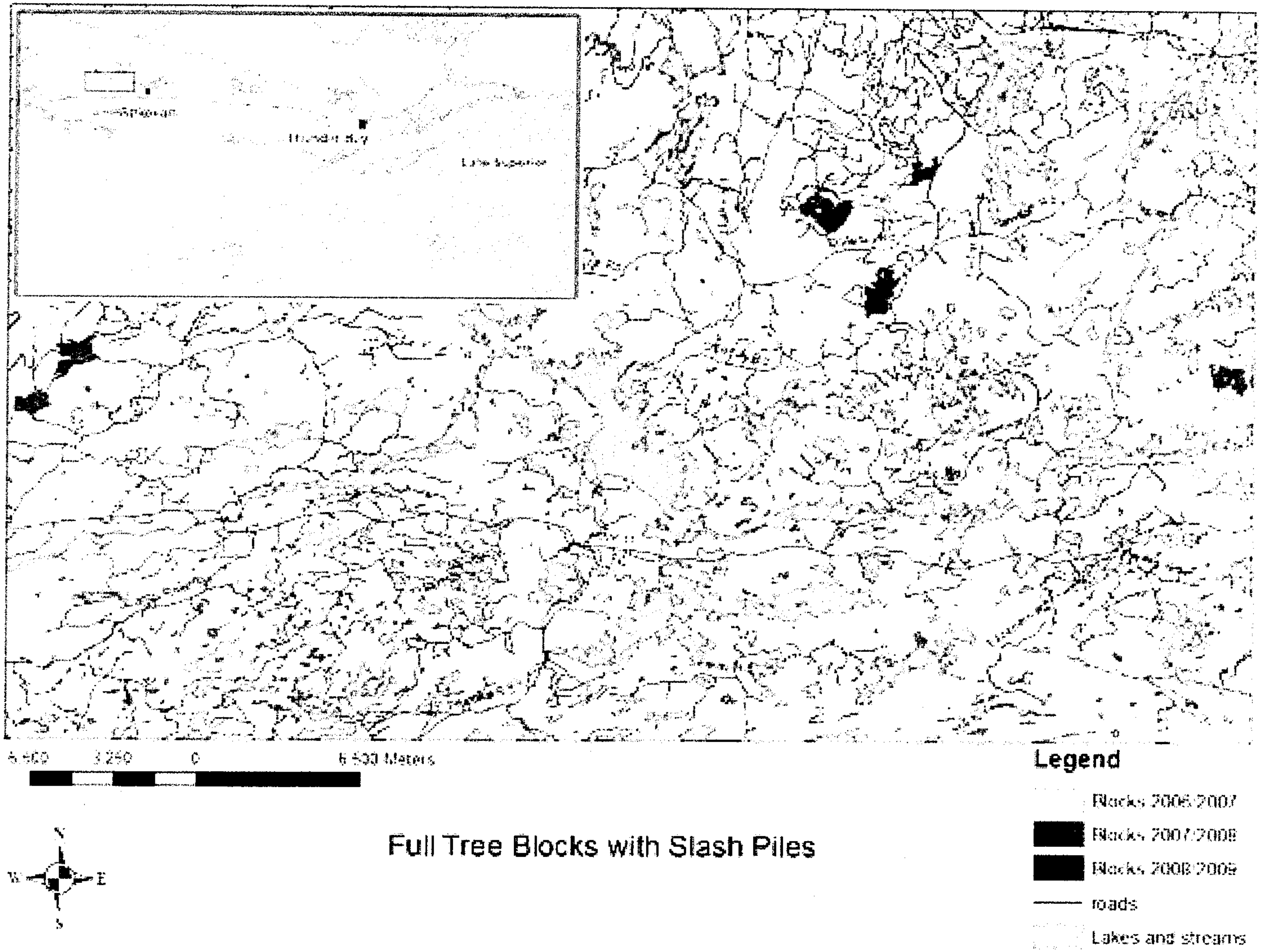


Figure 8. Map of the blocks with study roadside slash piles in northwestern Ontario.

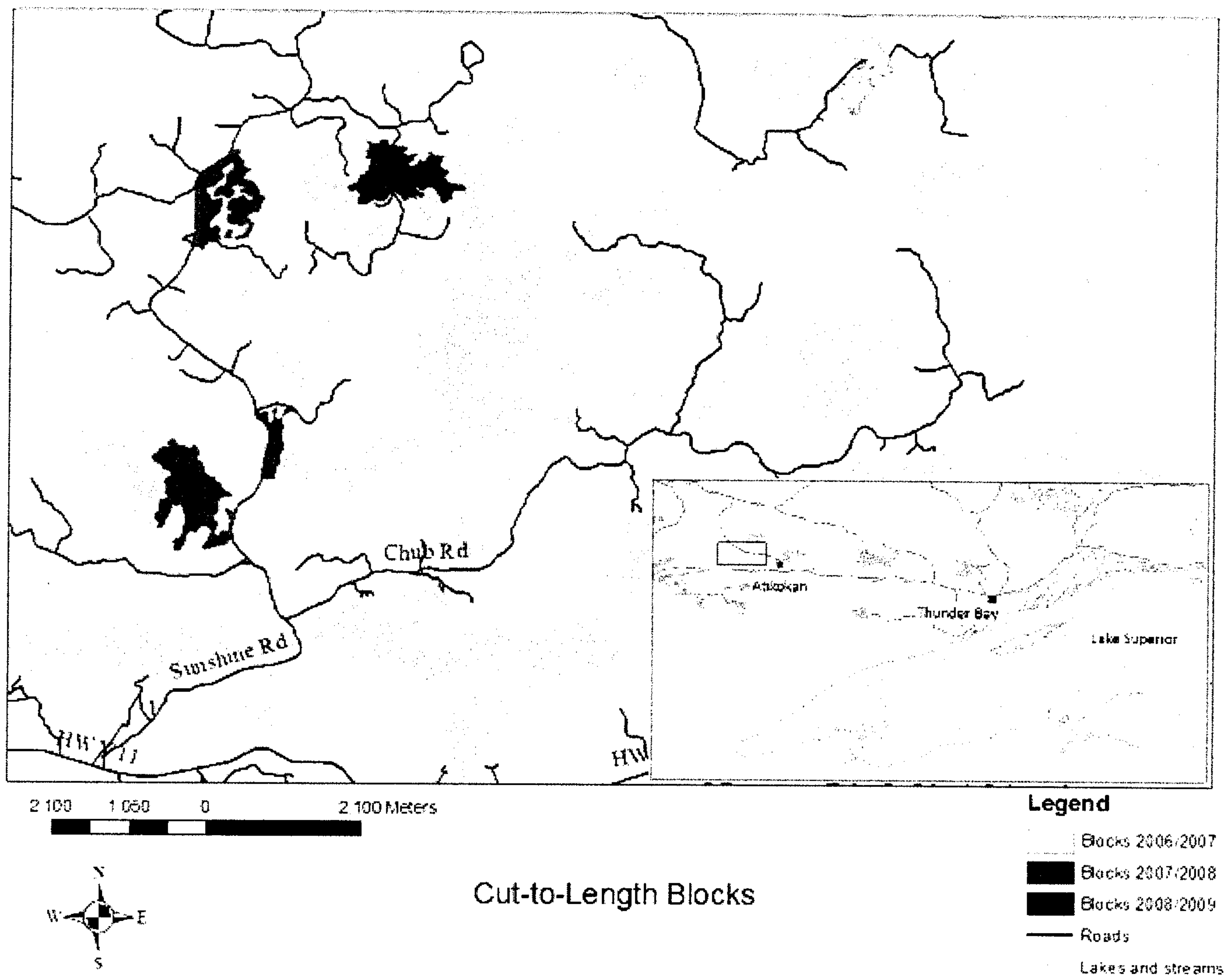


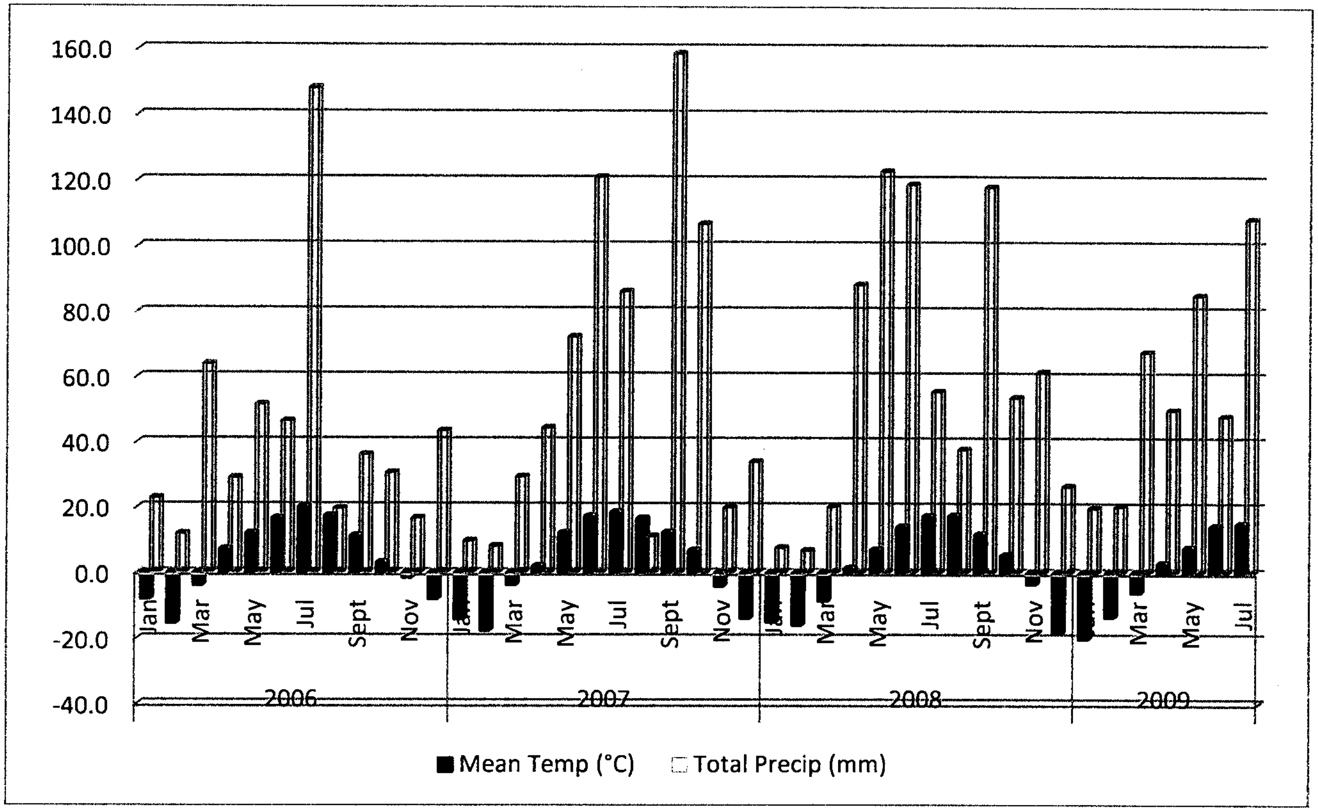
Figure 9. Map showing location of the cut-to-length study blocks in northwestern Ontario.

2.3.2. Weather Data

The mean monthly temperature and precipitation accumulation recorded by the Atikokan weather station (AUT) (Lat. 48^0 45.667′ N, Long. 91^0 37.683′W) during the storage period is displayed in Figure 10. The mean annual temperature was 2.7°C and the mean annual precipitation was 645 mm for the duration of the storage.

2.3.3. Experimental Design

The experiment layout and the location of slash piles are displayed in Table 4. Storage years included materials stored for 1, 2 and 3 drying seasons. The shape of the slash piles selected in the study fall either under the general category "half-section of sphere" or "half-ellipsoid" referred to as beehive and windrow, respectively. General shapes of piled woody debris have been outlined by Hardy (1996). Species were divided into the general categories of softwoods and hardwoods; softwoods included balsam fir, white spruce, black spruce, jack pine, while hardwood species included red maple, white birch and trembling aspen. The heights of the piles were recorded as being either greater or less than 2 m; the width ranged from 8 m to 16 m.



Source: Environment Canada (2009)

Figure 10. Mean monthly temperature and total monthly precipitation in Atikokan weather station (AUT).

Table 4. Experimental layout and location of the study slash piles.

Storage years	Shape	Species	Height*	Lat.	Long.
1	Windrow	Softwood	<2	48° 51' N	91° 58' W
1	Windrow	Softwood	>2	48° 51' N	91° 58' W
1	Windrow	Hardwood	<2	48° 47' N	91° 22' W
1	Windrow	Hardwood	>2	48° 47' N	91° 22' W
1	Beehive	Softwood	<2	48° 43' N	91° 51' W
1	Beehive	Softwood	>2	48° 43' N	91° 51' W
1	Beehive	Hardwood	<2	48° 47' N	92° 22' W
1	Beehive	Hardwood	>2	48° 44' N	92° 39' W
2	Windrow	Softwood	<2	48° 51' N	91° 54' W
2	Windrow	Softwood	>2	48° 51' N	91° 55' W
2	Windrow	Hardwood	<2	48° 46' N	92° 24' W
2	Windrow	Hardwood	>2	48° 43' N	91° 46' W
2	Beehive	Softwood	<2	48° 43' N	91° 54' W
2	Beehive	Softwood	>2	48° 43' N	91° 54' W
2	Beehive	Hardwood	<2	48° 46' N	91° 23' W
2	Beehive	Hardwood	>2	48° 46' N	91° 23' W
3	Windrow	Softwood	<2	48° 48' N	91° 56' W
3	Windrow	Softwood	>2	48° 44' N	91° 38' W
3	Windrow	Hardwood	<2	48° 47' N	92° 22' W
3	Windrow	Hardwood	>2	48° 47' N	92° 22' W
3	Beehive	Softwood	<2	48° 47' N	92° 22' W
3	Beehive	Softwood	>2	48° 43' N	91° 47' W
3	Beehive	Hardwood	<2	48° 46' N	92° 22' W
3	Beehive	Hardwood	>2	48° 47' N	92° 22' W

* >2 = higher than 2 m
<2 = lower than 2 m

Analysis of variance (ANOVA) test was carried out using the General Linear Method in SPSS to test the null hypothesis: harvest year, species, pile shape and pile height have no effect on the mean moisture content of slash piles. The variable diameter has been omitted from this model to maintain a balanced design. It is assumed that diameter is randomly distributed in the pile and its effect will be accounted for by the error term. The experimental design of the model is a full factorial design; the experimental units are 25 cm increment horizons in the piles. With six repetitions in each pile, the experiment size was 144. The linear model for this experiment is presented in Equation (4).

$$Y_{ijklm} = \mu + Y_i + T_j + S_k + H_l + YT_{ij} + YS_{ik} + YH_{il} + TS_{jk} + TH_{jl} + SH_{kl} + YTS_{ijk} + YTH_{ijl} + YSH_{ikl} + TSH_{jkl} + YTSH_{ijkl} + \epsilon_{(ijkl)m} \quad [4]$$

$i = 1,2,3 \quad j=1,2 \quad k=1,2 \quad l= 1,2 \quad m=6$

Where,

Y_{ijkl} = the average moisture content of pile from m^{th} replicate, l^{th} pile height, k^{th} species j^{th} pile type and i^{th} year.

μ = the grand mean

Y_i = the fixed effect of the i^{th} of three levels of Year

T_j = the fixed effect of the j^{th} of two levels of pile type

S_k = the fixed effect of the k^{th} of two levels of species

H_l = the fixed effect of the l^{th} of two levels of height

YT_{ij} = the interaction effect of i^{th} year with j^{th} pile type

YS_{ik} = the interaction effect of i^{th} year and k^{th} species

YH_{il} = the interaction effect of i^{th} year and l^{th} pile height

TS_{jk} = the interaction effect of j^{th} pile type and k^{th} species

TH_{jl} = the interaction effect of j^{th} pile type and l^{th} pile height

SH_{kl} = the interaction effect of k^{th} species and l^{th} pile height

YTS_{ijk} = the interaction effect of i^{th} year, j^{th} pile type k^{th} species

YTH_{ijl} = the interaction effect of i^{th} year, j^{th} pile type l^{th} pile height

YSH_{ikl} = the interaction effect of i^{th} year, k^{th} species l^{th} pile height

TSH_{jkl} = the interaction effect of j^{th} pile type, k^{th} species and l^{th} pile height

$YTSH_{ijkl}$ = the interaction effect of i^{th} year, j^{th} pile type, k^{th} species and l^{th} pile height

$\epsilon_{(ijkl)m}$ = the random effect of m^{th} rep within i^{th} year, j^{th} pile type, k^{th} species and l^{th} pile height

2.3.4. Slash Pile Selection

Burning of slash piles in the harvest blocks had been avoided for several years in anticipation of the biomass boiler in Fort Frances, Ontario. A list of blocks containing slash piles was obtained from the AbitibiBowater Inc. office in Fort Frances. This list included harvest blocks from three different AWS: 2006/2007, 2007/2008 and 2008/2009. The list was refined after visiting each block and eliminating blocks that did not contain slash piles. A rough inventory of pile shape, pile height and dominant species was prepared for blocks from each year; pile heights were measured using a laser hypsometer.

Slash piles that satisfy a particular combination in Table 4 were tallied together and numbered. Subsequently, a random number generator was used to select a pile from the tally; the procedure was repeated for all 24 combinations. Each of the slash piles were measured for MC at six 25 cm increment horizons. Data was collected in the summers of 2008 and 2009. The collection dates in the summer of 2008 extended from July 17 to July 30, and the dates for 2009 extended from May 18 to June 3.

2.3.4.1. Moisture content measurement

2.3.4.1.1. Slash pile surface measurement procedure

Using a compass, ribbon was laid in an east to west orientation on beehive type slash piles. On windrows, a location was randomly selected along the length of the windrow and ribbon placed along the width of the windrow at that particular location. All biomass material that intersected the ribbon at the surface of the pile was cut with a chainsaw at the point of the intersection to expose the complete diameter of the portion at the point of intersection. Protimeter Surveymaster Moisture Meter was used to measure the MC at various points on the cross section of the cut portion. The MC and species, as well as the diameter of the cross section were recorded. This procedure was continued for all biomass on the pile that was intersecting the ribbon. A number of samples were put in brown paper bags and brought to the lab to determine heat values and ash content. The diameter classes for samples collected from slash piles are: small (all samples less than or equal to 4 cm) and large (all samples greater than 4 cm).

2.3.4.1.2. Slash piles internal measurement procedure

Standing at the highest point of the slash pile where the ribbon was intersecting the slash pile, the slash pile was dissected vertically to a depth of 1.5 m using a chainsaw. It was done in a careful manner so that at least one cross-sectional face was undisturbed; scrap materials were dug out and thrown to the side. A measurement tape was hung from the top of the pile to the depth of 1.5 m and pink ribbon was used to divide the 1.5 m hole into 25 cm sections. At each 25 cm section, the MC and species were recorded for all exposed biomass. The MC was measured using moisture meter, and the diameter was measured using a diameter tape. Samples were collected from a 1.5 m depth, and returned to the lab to determine heat value and ash content. A picture of a typical pit excavation is shown in Figure 11.

Figure 11. A typical pit excavation for measurement of moisture content in slash piles.

2.3.4.2. Thermal value determination

The samples gathered during MC measurement were analyzed to determine if there was significant differences in the thermal value of logging residue in slash piles due to harvest year, location in pile, species and diameter. ANOVA test was carried out to test the null hypothesis: storage year, location in pile, species and diameter have no effect on the mean thermal values of logging residue. Pile type has been omitted from this model as there is no indication in the literature that pile type has an effect on the thermal value. The experimental design of the model is a full factorial design with 3 repetitions and an experiment size of 48. The linear model for this experiment is presented in Equation (5).

$$Y_{ijklm} = \mu + Y_i + L_j + S_k + D_l + YL_{ij} + YS_{ik} + YD_{il} + LS_{jk} + LD_{jl} + SD_{kl} + YLS_{ijk} + YLD_{ijl} + YSD_{ikl} + LSD_{jkl} + YLSD_{ijkl} + \epsilon_{(ijkl)m} \quad [5]$$

$i = 1,2 \quad j=1,2 \quad k=1,2 \quad l = 1,2,3,4 \quad m=1,2,3$

Where,
Y_{ijkl} = the mean thermal value of m^{th} replicate, l^{th} diameter, k^{th} species j^{th} location and i^{th} year.
μ = the grand mean
Y_i = the fixed effect of the i^{th} of three levels of Year
L_j = the fixed effect of the j^{th} of two levels of Location
S_k = the fixed effect of the k^{th} of two levels of species
D_l = the fixed effect of the l^{th} of four levels of diameter
YL_{ij} = the interaction effect of i^{th} year with j^{th} location
YS_{ik} = the interaction effect of i^{th} year and k^{th} species
YD_{il} = the interaction effect of i^{th} year and l^{th} diameter
LS_{jk} = the interaction effect of j^{th} location and k^{th} species
LD_{jl} = the interaction effect of j^{th} location and l^{th} diameter
SD_{kl} = the interaction effect of k^{th} species and l^{th} diameter
YLS_{ijk} = the interaction effect of i^{th} year, j^{th} location k^{th} species
YLD_{ijl} = the interaction effect of i^{th} year, j^{th} location l^{th} diameter
YSD_{ikl} = the interaction effect of i^{th} year, k^{th} species l^{th} diameter
LSD_{jkl} = the interaction effect of j^{th} location, k^{th} species and l^{th} diameter
$YLSD_{ijkl}$ = the interaction effect of i^{th} year, j^{th} location, k^{th} species and l^{th} diameter
$\epsilon_{(ijkl)m}$ = the random effect of m^{th} rep within i^{th} year, j^{th} location, k^{th} species and l^{th} diameter

2.3.4.2.1. Laboratory method for thermal value determination

A Parr 6200 Bomb Calorimeter at the Lakehead University Wood Science and Testing Facility (LUWSTF) was used in accordance with the LUWSTF Parr 6200 Bomb Calorimeter lab Manual to determine the heat values of the samples collected at the surface and 1.5 m depth of the slash pile. The samples consisting of main stem, branches and twigs were dried to moisture content of 10-20% (GW). After achieving the desired moisture level, the samples were ground using appropriate methods; stems were held firmly in collection basin and holes were drilled along the length of the log using appropriate sized spade bit and drill producing samples representative of the wood from bark to pith. Branches were secured tightly in a clamping shop table with a collection basin underneath. Appropriate sized spade bit, depending on the size of the branch, was used to drill holds along the length of the branch producing samples representative of the branch from bark to pith. Twigs were manually crumbled into small pieces. The material was allowed to dry further for 24-48 hours before running it through the large Wiley Mill followed by a mini Wiley mill.

A bone dry sample of known mass (~ 1g ± 0.5g) in pellet form was placed in the bomb which was then placed in the calorimeter. The calorimeter pressurizes the bomb with pure oxygen and is submerged under 2 l of distilled water of known temperature. The biomass in the bomb is ignited; the combustion raises the temperature of the bomb and consequently of the 2 l of water. The calorimeter gives an output of heat value in $MJ \cdot kg^{-1}$ based on the temperature change of the water taking into consideration the electrical input during ignition.

2.3.4.3. Ash content determination

The samples collected during MC measurement were also analyzed for ash content. ANOVA test was carried out to test the null hypothesis: harvest year, species and diameter have no effect on the mean ash content of logging residue. The experimental design of the model is a full factorial design with 3 repetitions and experiment size of 24. The model excludes pile type, height and location as there is no evidence that these factors have an effect on the ash content. The linear model for this experiment is presented in Equation (6).

$$Y_{ijklm} = \mu + Y_i + S_j + D_k + YS_{ij} + YD_{ik} + SD_{jk} + YSD_{ijk} + \epsilon_{(ijk)l} \qquad [6]$$

$i = 1,2 \quad j=1,2 \quad k=1,2 \quad l = 1,2,3$

Where,

Y_{ijkl} = the mean ash content of mth replicate, lth diameter, kth species jth location and ith year.

μ = the grand mean

Y_i = the fixed effect of the ith of three levels of Year

S_j = the fixed effect of the jth of two levels of species

D_k = the fixed effect of the kth of four levels of diameter

YS_{ij} = the interaction effect of ith year and jth species

YD_{ik} = the interaction effect of ith year and kth diameter

SD_{jk} = the interaction effect of jth species and kth diameter

YSD_{ijk} = the interaction effect of ith year, jth species kth diameter

$\epsilon_{(ijk)l}$ = the random effect of lth rep within ith year, jth species and kth diameter

2.3.4.3.1. Laboratory method for ash content determination

The ash content was determined according to procedures outlined in Sluiter *et al.* (2008). In accordance with the manual, crucibles were labelled and dried thoroughly by placing them in a muffle furnace at 575°C for 4 hours. The crucibles were then moved to a desiccator and weighed to the nearest 0.1 mg. The crucibles were reheated and cooled until a constant weight of ±0.3 mg was achieved. Samples were ground using the exact method used during thermal value determination. Bone dry biomass between 0.5-2.0 g was weighed and placed in a crucible. The crucibles were placed in a muffle furnace and a ramping program started as per the directions of Sluiter *et al.* (2008). The ramping program gradually elevates the temperature up to 575°C and maintains it for 180 minutes, burning the biomass in the crucible. The crucible is transferred into a desiccator and allowed to cool. The crucible is weighed and put back into the muffle furnace until a constant weight of ±0.3 mg is achieved. The ash is weighed to the nearest 0.1 mg. Percent ash content is determined using Equation (7).

$$\% \text{ Ash} = \frac{\text{Weight}_{\text{crucible and ash}} - \text{Weight}_{\text{crucible}}}{\text{Oven Dry Weight}_{\text{Sample}}} \text{ X } 100\% \qquad [7]$$

2.3.5. Cut-to-Length

2.3.5.1. Block selection

Similar to the slash pile list, a list of blocks harvested using the CTL method in AWS 2006/2007, 2007/2008 and 2008/2009 was acquired from AbitibiBowater Inc. The list was further divided into hardwood dominant and softwood dominant blocks. Both hardwood dominant blocks and softwood dominant blocks from each AWS were numbered in an ascending order and a random number generator was used to select two blocks, a hardwood dominant block and a softwood dominant block, from each

AWS. The experiment layout and the location of cut-to-length blocks are shown in Table 5. Maps of each of the selected blocks were printed and a pin dropped randomly on each map to locate starting point and traverse direction.

Table 5. Location of cut-to-length blocks and the experimental layout.

Storage years	Dominant Species	Lat. Long.
1	Softwood	48° 48' N91° 49' W
1	Hardwood	48° 48' N91° 49' W
2	Softwood	48° 47' N91° 56' W
2	hardwood	48° 45' N91° 57' W
3	Softwood	48° 47' N91° 54' W
3	Hardwood	48° 46' N91° 56' W

2.3.5.1. Moisture content

Another objective of the study was to determine if storage years and species led to a significant difference in the moisture content of logging residue in CTL blocks. ANOVA test was carried out to test the null hypothesis: harvest year and species have no effect on the mean moisture content of logging residue in CTL blocks. The experimental design of the model is a full factorial design with 20 repetitions and experiment size of 240. The linear model for this experiment is presented in Equation (8).

$$Y_{ijk}= \mu + Y_i + D_j + S_k + YD_{ij} + YS_{ik} + YSD_{ijk} + \epsilon_{(ijk)l} \qquad [8]$$

$i= 1,2,3$ $j=1,2$ $k=1, 2$ $l=20$

Where,

Y_{ijkl} = the green basis moisture content of k^{th} replicate, j^{th} species and i^{th} year.

μ = the grand mean

Y_i = the fixed effect of the i^{th} of three levels of year
D_j = the fixed effect of the j^{th} of two levels of diameter class
S_k = the fixed effect of the k^{th} of two levels of species
YD_{ij} = the interaction effect of i^{th} year with j^{th} diameter class
YS_{ik} = the interaction effect of i^{th} year with k^{th} species
YDS_{ijk} = the interaction effect of i^{th} year with j^{th} diameter and k^{th} species
$\epsilon_{(ij)k}$ = the random effect of l^{th} rep within k^{th} species, j^{th} diameter and i^{th} year

2.3.5.1.1 Field procedure

The data collection in CTL blocks took place in the period extending from July 30 to August 6, 2008. In the field, the randomly selected points were located using a Garmin GPS and a compass. From the starting point a 50 m chain was used to establish a straight line transect in the direction of the pin head. A chainsaw was used to cut all the LR that was intersecting the chain to expose its complete cross sectional diameter at the point of intersection. A Protimeter Surveymaster Moisture Meter was used to measure the MC at various points on the cross section of the cut piece ensuring all possible area of the cross-section was represented. Along with MC, the species and the diameter of the cross-section were recorded. Additionally, samples of various size and species were collected, and brought back to the lab for heat value and ash content determination. The diameter classes for samples collected from CTL blocks are: small (0-4 cm), and large (all samples greater than 4 cm).

2.3.5.2. Thermal value

Thermal values of samples collected from CTL blocks were also determined to test for variance between storage year, species and diameter. The null hypothesis tested was: harvest year, species and diameter have no effect on the mean thermal value of logging residue in CTL blocks. The experimental design of the model is a full factorial design with 3 repetitions and experiment size of 36. The linear model for this experiment is presented in Equation (9).

$$Y_{ijkl} = \mu + Y_i + S_j + D_k + YS_{ij} + YD_{ik} + SD_{jk} + YSD_{ijk} + \epsilon_{(ijk)l} \qquad [9]$$

$i = 1,2,3 \quad j=1,2 \quad k=1,2 \quad l=3$

Where,

Y_{ijkl} = the thermal value of kth replicate, jth species and ith year.

μ = the grand mean

Y_i = the fixed effect of the ith of three levels of year

S_j = the fixed effect of the jth of two levels of species

D_k = the fixed effect of the kth of four levels of diameter

YS_{ij} = the interaction effect of ith year with jth species

YD_{ik} = the interaction effect of ith year with kth diameter

SD_{jk} = the interaction effect of jth species with kth diameter

YSD_{ijk} = the interaction effect of ith year with jth species and kth diameter

$\epsilon_{(ijk)l}$ = the random effect of lth rep within kth diameter, jth species and ith year

2.3.5.3. Ash content

The ash content values of logging residue in CTL blocks were also investigated to determine if significant differences exist. ANOVA test was carried out to test the null hypothesis: harvest year, species and diameter have no effect on the mean ash content of logging residue in CTL blocks. The experimental design of the model is a full factorial design with 2 repetitions and experiment size of 24. The linear model for this experiment is presented in Equation (10).

$$Y_{ijkl} = \mu + Y_i + S_j + D_k + YS_{ij} + YD_{ik} + SD_{jk} + YSD_{ijk} + \epsilon_{(ijk)l} \qquad [10]$$

$i = 1,2,3 \quad j=1,2 \quad k = 1, 2 \quad l = 2$

Where,

Y_{ijkl} = the mean ash content of l^{th} replicate, k^{th} diameter, j^{th} species and i^{th} year.
μ = the grand mean
Y_i = the fixed effect of the i^{th} of three levels of year
S_j = the fixed effect of the j^{th} of two levels of species
D_k = the fixed effect of the k^{th} of four levels of diameter
YS_{ij} = the interaction effect of i^{th} year with j^{th} species
YD_{ik} = the interaction effect of i^{th} year with k^{th} diameter
SD_{jk} = the interaction effect of j^{th} species with k^{th} diameter
YSD_{ijk} = the interaction effect of i^{th} year with j^{th} species and k^{th} diameter
$\epsilon_{(ijk)l}$ = the random effect of l^{th} rep within k^{th} diameter, j^{th} species and i^{th} year

2.4. RESULTS & DISCUSSION

2.4.1. Moisture Content

A summary of moisture content observed in slash piles is presented in Table 6 along with the standard deviations. The average moisture content on a GW basis ranged from 14.1% to 35%. The average moisture content observed in this study is lower than values observed in the Scandinavian countries. (Petterson and Nordfjell 2007; Nurmi 1999; jirjis 2005; Lehtikangas 2001). The lower moisture content achieved in this study can be attributed to the continental climate in Northern Ontario (Gamble 1997). Hot summers recorded in our study area (Figure 10) lead to feedstock drier than those presented in studies above. Comparatively, in the Scandinavian countries, the climate is moderated due to maritime influences and thus do not reach similar extremes.

A summary of the ANOVA is presented in Table 7 to test the hypothesis that logging residue storage years, pile shape, species and height do not affect the mean moisture content.

Table 6. Summary of average moisture content (GW) values from top 1.5 m of roadside slash piles.

Drying Seasons	Shape	Species	Pile Height <2 m	Standard Deviation	>2 m	Standard Deviation
1	Windrow	Softwood	20.9	2.56	20.3	3.42
		Hardwood	26.8	3.78	29.7	7.81
	Beehive	Softwood	27.8	4.27	22.9	1.56
		Hardwood	35.0	7.77	32.4	2.00
2	Windrow	Softwood	23.6	2.28	21.5	2.72
		Hardwood	16.5	2.74	22.1	4.25
	Beehive	Softwood	14.1	1.25	16.9	4.01
		Hardwood	26.9	3.37	30.9	3.87
3	Windrow	Softwood	18.2	0.78	18.7	6.76
		Hardwood	21.8	2.90	22.6	5.19
	Beehive	Softwood	16.6	2.01	18.9	4.16
		Hardwood	29.4	14.34	31.6	5.12

Table 7. Summary of analysis of variance on moisture content values of logging residue from roadside slash piles.

Source	d.f	Sum of Squares	Mean Square	F value	Sig[a]
Storage years	2	837	419	16.76	***
Shape	1	409	409	16.36	***
Species	1	1817	1817	72.68	***
Height	1	29	29	1.16	ns
Storage years * Shape	2	90	45	1.80	ns
Storage years * Species	2	74	37	1.48	ns
Shape * Species	1	701	701	28.04	***
Storage years * Shape * Specie	2	381	191	7.64	**
Error	131	3276	25		

a - ns indicates not significant

* indicates significance at 0.05 level

** indicates significance at 0.01 level

*** indicates significance at 0.001 level

A summary of moisture content observed in the cut-to-length blocks is presented in Table 8 along with the standard deviation values. Logging residue in cut-to-length blocks show a higher variation in moisture content than logging residue in slash piles, the average moisture content in GW ranged from 11.9% to 40.7%. A summary of analysis of variance performed to test the hypothesis that logging residue storage years, diameter and species does not affect the mean moisture content is presented in Table 9.

Table 8. Summary of average moisture content (% green basis) values of logging residue from cut-to-length blocks.

Storage Years	Species	Diameter*			
		Large	Standard Deviation	Small	Standard Deviation
1	Softwood	26.5	13.9	18.0	4.8
	Hardwood	40.7	17.8	35.1	22.2
2	Softwood	20.3	8.8	11.9	1.4
	Hardwood	35.1	19.8	28.6	17.8
3	Softwood	27.9	15.4	16.2	5.6
	Hardwood	38.0	15.2	19.8	10.2

*Large = > 4 cm in diameter
Small = ≤ 4 cm in diameter

Table 9. Summary of analysis of variance on moisture content values of logging residue from cut-to-length blocks.

Source	d.f	Sum of Squares	Mean Square	F value	Sig[a]
Storage years	2	1616	808	4.03	*
Diameter	1	5794	5795	28.90	***
Species	1	9676	9676	48.26	***
Storage years * Diametei	2	780	390	1.94	ns
Storage years * Species	2	1042	521	2.59	ns
Diameter * Species	1	5	5	0.02	ns
Error	230	46115	200		

a - ns indicates not significant
* indicates significance at 0.05 level
** indicates significance at 0.01 level
*** indicates significance at 0.001 level

2.4.1.1. Effect of storage duration

The data indicates that storage period has a significant effect on the mean MC of slash piles and also of logging residue spread in the cutover. Post hoc analysis of slash pile MC using Duncan test showed that, year 1 piles displayed significantly higher (*p*<0.001) MC of 27.0% (GW) compared to year 2 and 3 piles which displayed an average MC of 21.9% (GW) as shown in Figure 12

CTL blocks showed a comparable trend, logging residue from year 1 showed significantly higher (*p*<0.05) MC with MC value of 30.1 % (GW). Year 2 and year 3 had an average MC of 24.7% (GW) as shown in Figure 13.

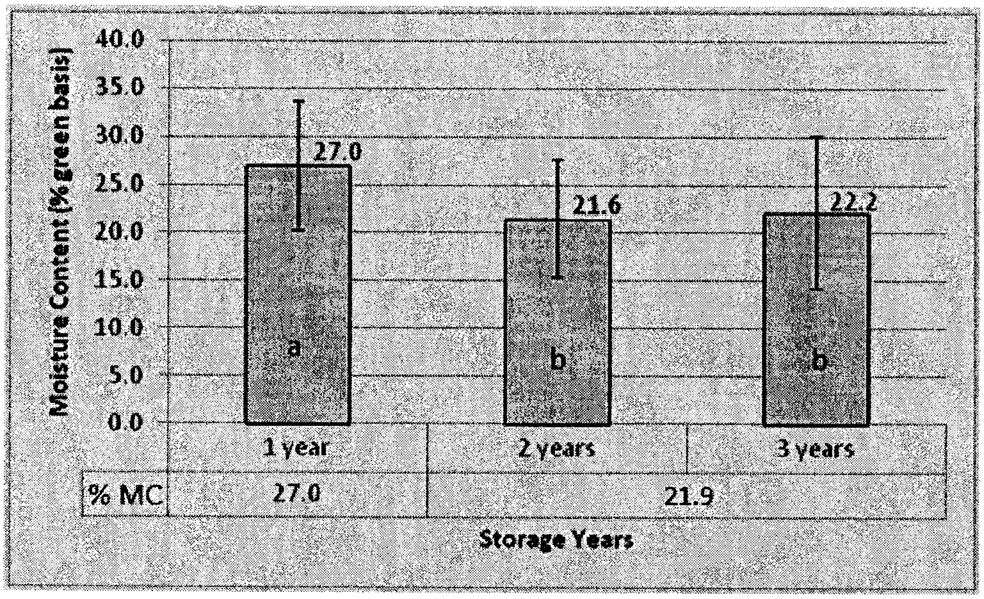


Figure 12. Average moisture content of logging residue in roadside slash piles displayed against storage years. Bars with same letters signify storage years that are not significantly different from each other. The error bars show the standard deviation.

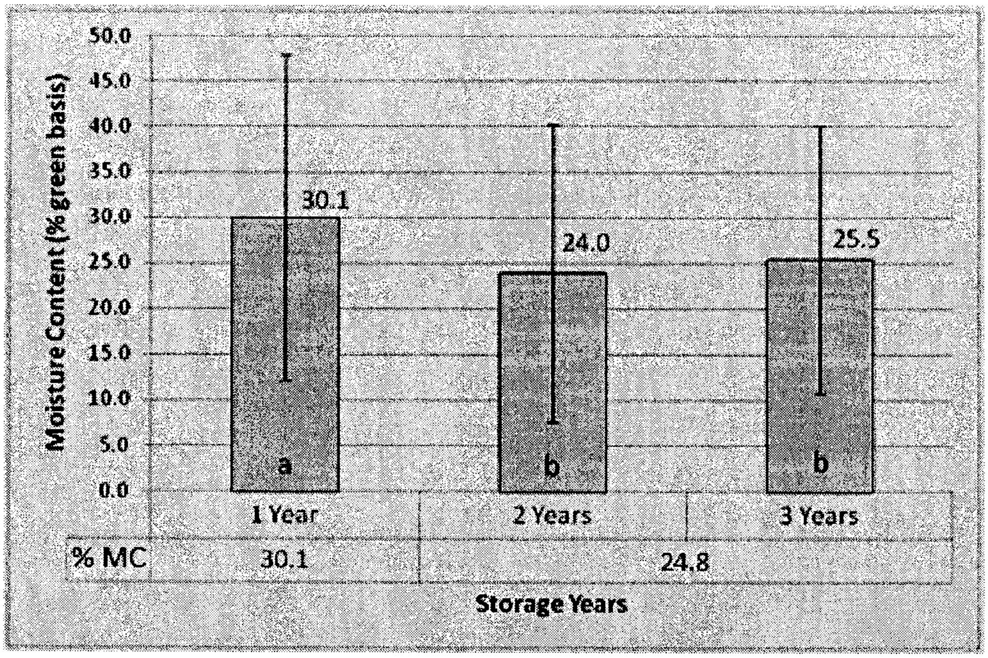


Figure 13. Average moisture content of logging residue in cut-to-length displayed against storage years. Bars with same letters signify storage years that are not significantly different from each other. The error bars show the standard deviation.

Once cut, green wood starts to lose moisture quickly at first as it loses free water and then at a slower rate for bound water (Shelton and Shapiro 1977). The moisture content gradually approaches an equilibrium state that fluctuates with temperature and relative humidity (Siau 1995). It is the hygroscopic nature of cell walls that allows the equilibrium moisture content to fluctuate in this manner. Our results suggests that the average MC of logging residue drops further in the second drying season, indicating that equilibrium moisture content itself decreases further. Our results are similar to the trends found by Millet (1953), Hall and Rudolph (1957) and Truman (1959) on pulpwood drying rates.

The hygroscopicity of the cell wall is due to the presence of hydroxyl groups (Esteban *et al.* 2005; Walker 2006). In the amorphous regions, there is irregularity in the molecule arrangement leaving accessible hydroxyl groups for bonding with water. Of course when the cell is laid down, it is done so in the presence of water. Upon removal of water from cell walls, many of the hydroxyl groups form new hydrogen bonds among themselves that may not be broken when remoistened. Thus fewer sites are available for bonding with water. Esteban *et al.* (2005) has defined this phenomenon of loss of hygroscopic response as hygroscopic ageing.

2.4.1.2. Effect of Species

Analysis of variance reveals that species had a significant effect ($p<0.001$) on the mean MC value of logging residue in both slash piles and cut-to-length blocks as shown in Table 7 and Table 9. In both slash piles and CTL blocks, softwoods produced lower moisture content than hardwoods as shown in Figure 14 and Figure 15 with one exception. In Figure 14, year 2 windrow hardwood piles display lower moisture content than softwood piles, however the difference in the MC values are not statistically significant.

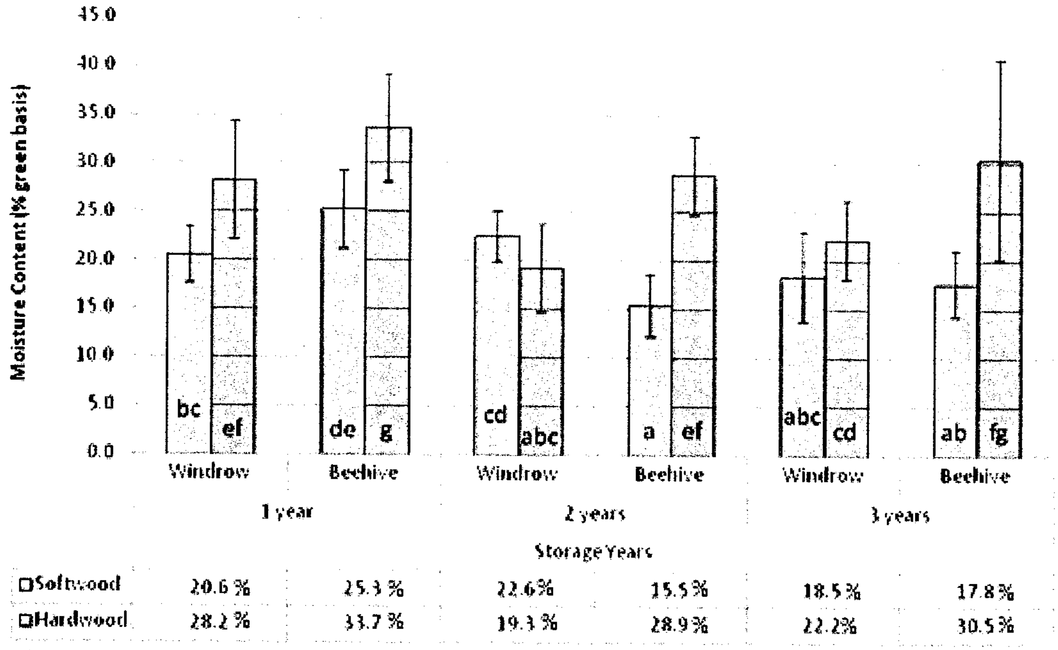


Figure 14. Average moisture content of logging residue from roadside slash piles displayed against interaction of storage years, pile shape and species. Bars with no common letters are significantly different from each other. The error bars show the standard deviation.

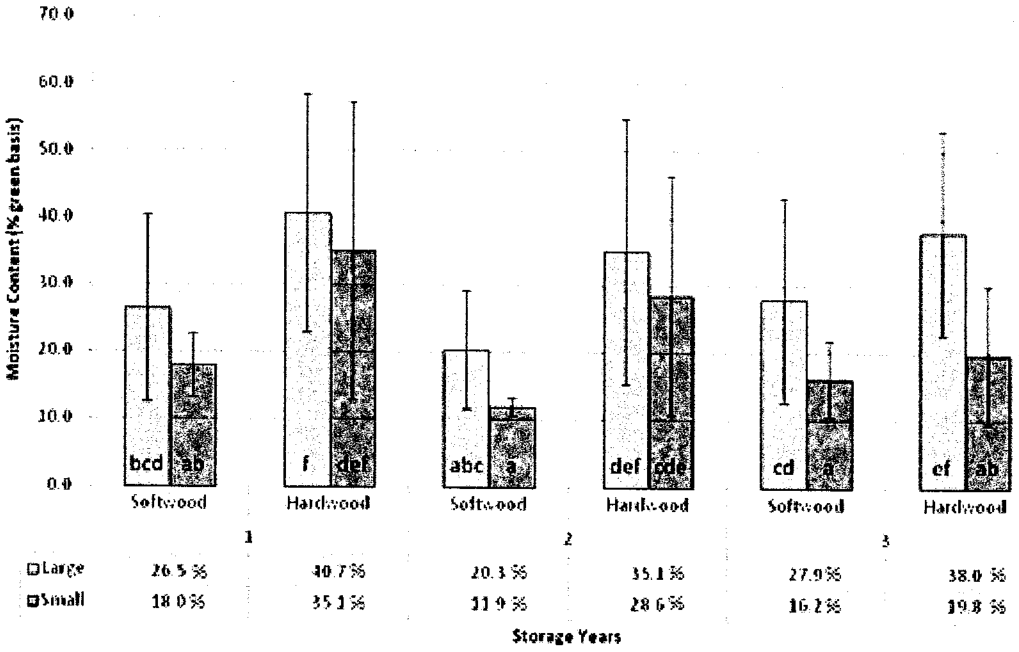


Figure 15. Average moisture content of logging residue from cut-to-length blocks displayed against interaction of storage years, species and diameter. "Large" represent stems with diameter larger than 4 cm and "small" represents diameter equal to or less than 4 cm. Bars with no common letters are significantly different from each other. The error bars show the standard deviation.

The lower MC values displayed by softwood species is best explained by the differences in the chemical composition and anatomical construction between hardwood and softwood species. In hardwoods, hemicelluloses constitute approximately 25-40% as opposed to 20-30% in softwoods (Siau 1995). Hemicellulose is the most hygroscopic component of cell wall followed by cellulose and lignin (Christensen and Kelsey 1959). Consequently, the cell walls of hardwoods will have more potential bonding sites available for water than softwoods. Also, the majority of pits in softwood contain tori that aspirate in the earlywood of sapwood once MC is below FSP impeding transportation (Siau 1995). Such pit aspiration does not occur in hardwood sapwood due to the lack of tori in their pits thus hardwoods can be more hygroscopic.

An added factor that may have contributed to the lower MC values in softwoods is transpiration drying (Angus-Hankin *et al.* 1995). The stomata of the leaves and needles are the main pathways for evaporation of moisture from a living tree (Raven *et al.* 1999). Once cut, the stomates close and transpiration is reduced significantly especially in conifers (Perem 1968). However it was observed that needles were intact in softwoods for longer durations than leaves on hardwoods. A similar observation was made by Rogers (1981) and Simola and Makela (1976); this would allow softwoods a longer time frame for transpiration drying thus a greater overall reduction in moisture.

2.4.1.3. Effect of Pile Height

Slash pile height showed no significant effect on the MC (Table 7). However, since the measurement was only performed to a depth of 1.5 m, no conclusions on the material below this depth can be made. In the literature on pile heights, Pettersson and Nordfjell (2007) and Jirjis (1995) report that smaller piles lose moisture rapidly when the vapour pressure deficit of the ambient air is high in the summer. However, the reports also state that when the temperature and RH drop, smaller piles regain moisture more rapidly.

2.4.1.4. Effect of Pile Shape

There was a significant effect ($p<0.001$) of pile shape on the MC of logging residue in slash piles as shown in Table 7. In addition, the interaction between storage year, shape and species is significant ($p<0.01$); the interaction graph is displayed in Figure 14. With regard to hardwoods, beehives display higher MC values than windrows in all storage years. Similar trends are not prevalent in slash piles of softwoods; in storage year 1, windrow piles show lower moisture content than beehive, in year 2 beehive piles show the lower moisture content and in year 3 the values are equivalent.

The lower moisture values displayed by windrows can be attributed to the greater surface area to volume ratio compared to beehive piles. In a study conducted by Hall and Rudolph (1957) on jack pine pulpwood piles, the moisture content fluctuation was much higher in the exposed wood than the inside wood. Also, the widths of windrow piles are much smaller compared to beehive piles; smaller width translates to less resistant to airflow, leading to faster drying of the piles.

The significant interaction observed in Table 7 and displayed in Figure 14 is most likely due to the level of compaction in the piles. Hardwood piles had a greater amount of void space compared to softwood piles. The more pronounced branching of hardwoods allows less compaction hence there is a higher percentage of void space in hardwood piles which translates to a lower airflow resistance by hardwood piles. Therefore in hardwood piles, beehives show a higher MC than windrows. However, in softwood piles, the reduced void space leads to higher airflow resistance especially in the beehive piles. Consequently, majority of logging residue in softwood beehive piles is protected from interface with the ambient air; it takes longer period for logging residue in these piles to reach EMC but once it is achieved, the fluctuations occur at much slower rate compared to windrow piles.

2.4.2. Thermal Value

A summary of thermal values and the corresponding standard deviation of samples from slash piles of both types, windrows and beehives, are presented in Table 10. The values ranged from 19.9 to 23.1 $MJ \cdot kg^{-1}$. Table 11 summarizes an analysis of variance performed to test the hypothesis that logging residue storage years, location in pile, species and diameter do not affect the mean thermal value.

Table 10. Summary of average thermal values in MJ·kg^{-1} of logging residue from roadside slash piles.

Drying Seasons	Location*	Species	Diameter**			
			Small	Standard Deviation	Large	Standard Deviation
2	Inside Pile	Softwood	21.2	0.4	22.4	0.5
		Hardwood	20.3	0.6	21.7	0.8
	Surface	Softwood	21.2	1.0	22.3	0.5
		Hardwood	20.4	0.5	20.9	0.9
3	Inside Pile	Softwood	20.8	1.0	23.1	0.2
		Hardwood	20.0	0.0	21.4	0.4
	Surface	Softwood	19.9	0.2	21.7	1.2
		Hardwood	20.7	1.0	22.5	1.1

* Inside pile is logging residue samples from depth of 1.5 m

**Small = ≤ 4 cm diameter, Large = > 4 cm diameter

Table 11. Summary of analysis of variance on thermal values of logging residue from roadside slash piles.

Source	d.f	Sum of Squares	Mean Square	F value	Sig[a]
Storage years	1	0.009	0.009	0.018	ns
Location	1	0.370	0.370	0.729	ns
Species	1	3.387	3.387	6.674	*
Diameter	1	24.980	24.980	49.219	***
Storage years * Location	1	0.002	0.002	0.005	ns
Storage Years * Species	1	1.689	1.689	3.328	ns
Location * Species	1	2.324	2.324	4.579	*
Storage year * Location * Specie	1	4.434	4.434	8.736	*
Storage year * Diameter	1	1.651	1.651	3.253	ns
Location * Diameter	1	0.274	0.274	0.540	ns
Species * Diameter	1	0.326	0.326	0.642	ns
Error	36	18.271	0.508		

a - ns indicates not significant

* indicates significance at 0.05 level

** indicates significance at 0.01 level

*** indicates significance at 0.001 level

A summary of thermal values and the corresponding standard deviation values of logging residue from cut-to-length blocks is presented in Table 12. The values ranged from 19.5 to 22.8 MJ·kg^{-1}. Table 13 summarizes the result from the analysis of variance performed to test the hypothesis that logging residue storage years, species and diameter do not affect the mean thermal value. Only diameter shows significant difference (p<0.001) in the analysis.

Table 12. Summary of average thermal values in MJ·kg^{-1} of logging residue from cut-to-length blocks.

Storage Years	Species	Diameter*			
		Large	Standard Deviation	Small	Standard Deviation
1	Softwood	20.1	0.12	21.3	0.06
	Hardwood	20.4	0.22	21.4	0.57
2	Softwood	21.6	1.86	22.0	2.10
	Hardwood	20.2	0.83	20.8	0.45
3	Softwood	19.5	0.50	22.8	1.76
	Hardwood	20.7	0.89	22.1	0.37

*Large = > 4 cm in diameter
Small = ≤ 4 cm in diameter

Table 13. Summary of analysis of variance on thermal values of logging residue from cut-to-length blocks.

Source	d.f	Sum of Squares	Mean Square	F value	Sig[a]
Storage years	2	1.366	0.683	0.613	ns
Diameter	1	15.393	15.393	13.815	***
Species	1	0.640	0.640	0.574	ns
Storage years * Diameter	2	4.948	2.474	2.220	ns
Storage Years * Species	2	4.669	2.334	2.095	ns
Diameter * Species	1	0.728	0.728	0.654	ns
Error	26	28.970	1.114		

a - ns indicates not significant
* indicates significance at 0.05 level
** indicates significance at 0.01 level
*** indicates significance at 0.001 level

2.4.2.1. Effect of species

In slash piles (Table 11), there was a significant difference in thermal value between species, but not in the CTL blocks (Table 13). Additionally, species had an interaction effect with storage years and location in pile; the interaction graph is displayed in Figure 16. Softwood constantly showed slightly higher thermal value than hardwoods with one exception: year 3 hardwoods at the surface of the piles showed higher average thermal value than softwoods but the difference was not significantly different. The highest average thermal value was displayed by softwoods from inside of the pile (1.5 m) and the lowest value was displayed by year 2 hardwoods at the surface of the piles.

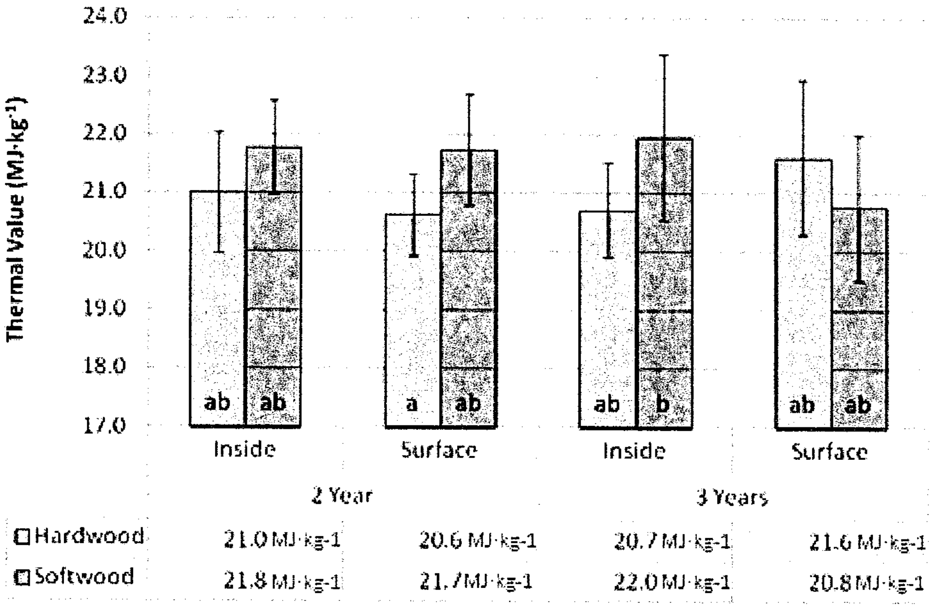


Figure 16. Average thermal values of logging residue from roadside slash piles displayed against interaction of storage years, location in piles and species. "Inside" represent samples from depth of 1.5 m and surface represents samples from the surface of the piles. Bars with no common letters are significantly different from each other. The error bars show the standard deviation.

The higher thermal value per kg displayed by softwoods can be attributed to the higher percentage of lignin and resin present in softwoods compared to hardwoods (Hakkila 1989; Plomion *et al.* 2001). Lignin and resins have considerably higher thermal values than cellulose and hemicellulose (GCEP 2005). Furthermore, the materials studied being branches, will contain higher percentage of reaction wood (Nurmi 1993). In softwoods, reaction wood contains a higher percentage of lignin than normal wood, meanwhile the opposite is true for hardwoods (Plomion *et al.* 2001; Bowyer *et al.* 2007).

2.4.2.2. Effect of stem diameter

Diameter led to significant difference ($p<0.001$) in the mean thermal value in both FT roadside slash piles (Table 11) and logging residue within cut-to-length blocks (Table 13). Smaller diameter branches display higher thermal values than larger diameter branches in both cases. Similar results were observed by Singh and Kostecky (1986) in samples collected in Manitoba. In softwoods, the higher thermal values in smaller samples can once again be attributed to the presence of compression wood and also a higher percentage of bark. The percentage of bark increases sharply as the branch diameter decreases (Hakkila 1989; Wellwood 1979). Bark generally has a higher heat value than stem wood because it is richer in lignin, resin, terpenes and other combustable elements (Hakkila 1989). In hardwoods, although smaller branches contain lower amount of lignin due to the presence tension wood, lignin content in hardwood bark is three to four fold compared to softwood bark (Nurmi 1993). The higher percent of lignin in bark coupled with the fact that there is a greater percentage of bark gives smaller branches the higher thermal value.

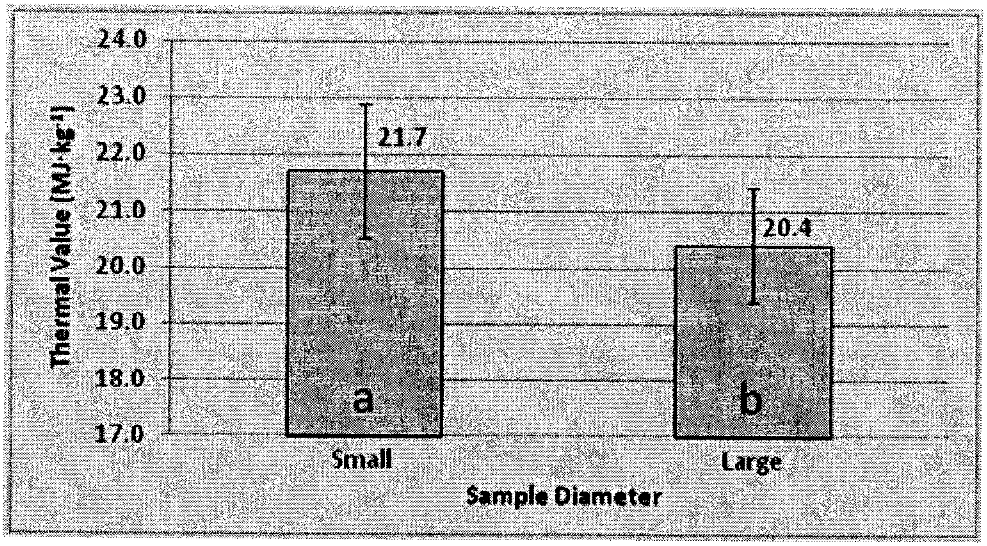


Figure 17. Average thermal values of logging residue in cut-to-length blocks piles displayed against sample diameter. "Large" represent stems with diameter larger than 4 cm and "Small" represents diameter equal to or less than 4 cm. Bars with no common letters are significantly different from each other. The error bars show the standard deviation.

2.4.2.4. Effect of storage duration

There is no significant difference in the mean thermal values of logging residue due to storage durations 1 to 3 years in slash piles (Table 11) or cut-to-length logging residue (Table 13). Hakkila (1989) mentions that although the heat value of logging residue changes during storage, the change is insignificant. This can be accredited to low MC which limits microbial activities thus decay of wood. Decay in wood can be initiated only at MC of over 26-32% dry mass basis (Hudson 1992).

2.4.3. Ash Content

A summary of ash content and the corresponding standard deviation values of logging residue from roadside slash piles are presented in Table 14. The values ranges from 2.7% to 8.4%. There was a noticeable difference in the ash content between large diameter samples and small diameter samples. Table 15 summarizes the analysis of variance performed to test the hypothesis that years stored, species and diameter have no effect on the mean ash content.

Table 14. Summary of average ash content values of logging residue samples from roadside slash piles.

Storage Years	Species	Diameter*			
		Large	Standard Deviation	Small	Standard Deviation
1	Softwood	3.5	0.29	3.8	0.20
	Hardwood	2.7	0.88	8.4	0.22
2	Softwood	4.9	0.63	6.1	0.59
	Hardwood	4.6	0.96	7.6	0.16

*Large = > 4 cm in diameter
Small = ≤ 4 cm in diameter

Table 15. Summary of analysis of variance on ash content values of logging residue samples from roadside slash piles.

Source	d.f	Sum of Squares	Mean Square	F value	Sig[a]
Storage years	1	0.970	0.970	2.853	ns
Species	1	1.118	1.118	3.288	ns
Diameter	1	4.450	4.450	13.088	*
Storage Years * Species	1	0.291	0.291	0.856	ns
Storage years * Diameter	1	0.123	0.123	0.362	ns
Species * Diameter	1	2.144	2.144	6.306	*
Error	17	5.776	0.340		

a - ns indicates not significant
* indicates significance at 0.05 level
** indicates significance at 0.01 level
*** indicates significance at 0.001 level

A summary of ash content and the corresponding standard deviation values of logging residue from cut-to-length blocks are presented in Table 16; the values ranges from 0.4% to 4.2%. Once again the difference in the ash content between large diameter samples and small diameter samples is noticeable. A summary of analysis of variance performed to test the hypothesis that years stored, species and diameter has no effect on the mean ash content is presented in Table 17.

Table 16. Summary of average ash content values of logging residue samples from cut-to-length blocks.

Storage Years	Species	Diameter*			
		Large	Standard Deviation	Small	Standard Deviation
1	Softwood	2.6	1.9	3.5	0.5
	Hardwood	1.7	0.2	4.2	0.0
2	Softwood	0.7	0.6	2.1	1.2
	Hardwood	1.9	0.0	4.2	0.2
3	Softwood	0.4	0.1	1.7	1.0
	Hardwood	1.5	1.8	1.8	0.2

*Large = > 4 cm in diameter
Small = ≤ 4 cm in diameter

Table 17. Summary of analysis of variance on ash content values of logging residue samples from cut-to-length blocks

Source	d.f	Sum of Squares	Mean Square	F value	Sig[a]
Storage years	2	11.254	5.627	6.505	*
Species	1	2.905	2.905	3.358	ns
Diameter	1	12.514	12.514	14.467	*
Storage Years * Species	2	3.015	1.507	1.742	ns
Storage years * Diameter	2	1.208	0.604	0.698	ns
Species * Diameter	1	0.413	0.413	0.477	ns
Error	14	12.103	0.865		

a - ns indicates not significant
* indicates significance at 0.05 level
** indicates significance at 0.01 level
*** indicates significance at 0.001 level

2.4.3.1. Effect of storage duration

Storage years showed no significant difference in the ash content of slash piles (Table 15) however in cut-to-length blocks (Table 17), storage years did show a significant difference (*p*<0.01) in the ash content values. Figure 18 displays ash contents of logging residue material from cut-to-length blocks against storage years. The percentage ash content has a decreasing tendency with the number of storage years. Storage years 1 and 3 have values significantly different (p<0.05) from each other but neither of the year show a significant difference from year 2.

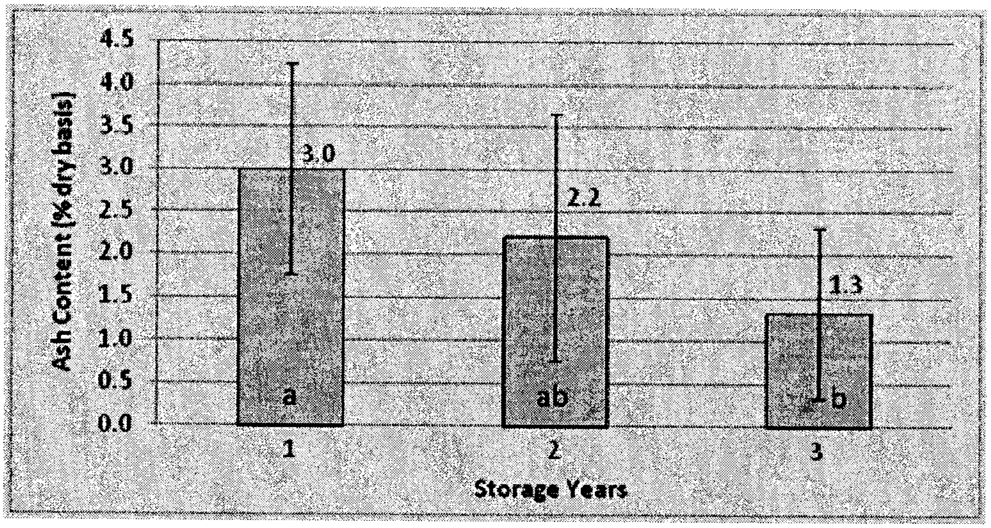


Figure 18. Average ash content of logging residue samples from cut-to-length blocks displayed against storage years. Bars with no common letters are significantly different from each other. The error bars show the standard deviation.

The significant difference caused by storage year on the ash content of cut-to-length logging residue is most likely due to the leaching of nutrients and other minerals from biomass. Similar significance due to storage duration was not observed in slash piles because the majority of logging residue is protected from weather factors. In cut-to-length blocks, the majority of logging residue is exposed to environmental factors resulting in leaching of elements by rainfall (Vamvuka *et al.* 2008; Jenkins *et al.* 1998).

Although not significant, ash content of slash piles shows a trend opposite to that observed in the cut-to-length blocks. Samples from year 2 show higher values than samples from year 1 with an exception, small diameter hardwood samples showed lower value for year 2. Petterson and Nordfjell (2007) report on trials, mainly from the

Scandinavian countries, which have shown similar increase in the ash content. Lehtikangas (2001) speculates the increase in ash content could be due to substance loss during storage. However, it must be reiterated that the difference in ash content between storage years was not statistically significant.

2.4.3.2. Effect of species and diameter

Diameter had a significant effect ($p<0.05$) on the mean ash content of logging residue from both slash piles and cut-to-length blocks. There was also an interaction effect between diameter and species in logging residue from slash piles; Figure 19 illustrates the interaction effect. Large diameter branches show lower ash content than small diameter branches. In large branches, softwoods show higher ash content but in small branches hardwoods show higher ash content than softwoods.

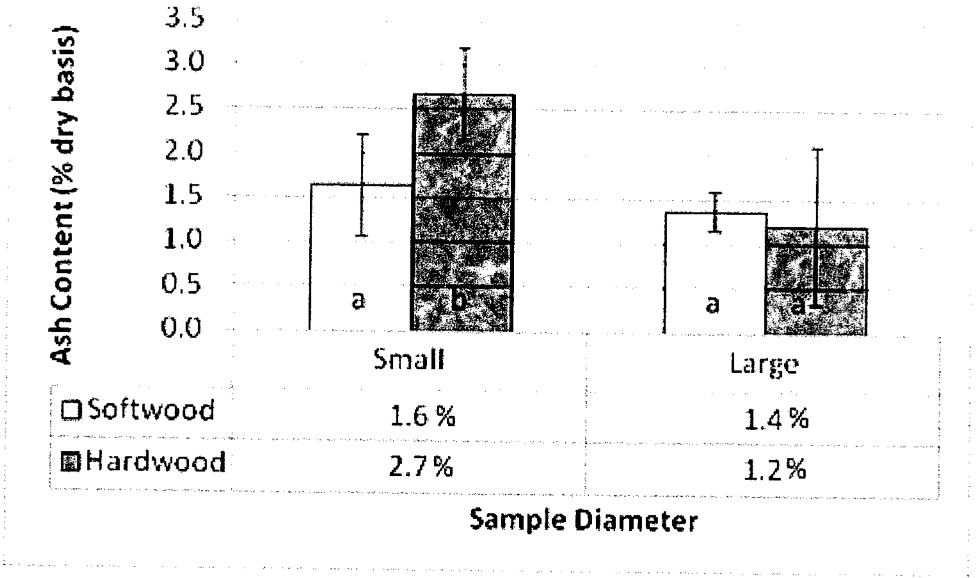


Figure 19. Average ash content of logging residue samples from roadside slash piles displayed against interaction of storage years and sample diameter. "Large" represent stems with diameter larger than 4 cm and "small" represents diameter equal to or less than 4 cm. Bars with no common letters are significantly different from each other. The error bars show the standard deviation.

Figure 20 illustrates the interaction of species and diameter in the cut-to-length blocks. Since the interaction was not significant, the translation of the figure is straightforward: softwood shows lower ash content than hardwood and smaller diameter branches show significantly higher ash content (p<0.05) than larger diameter branches.

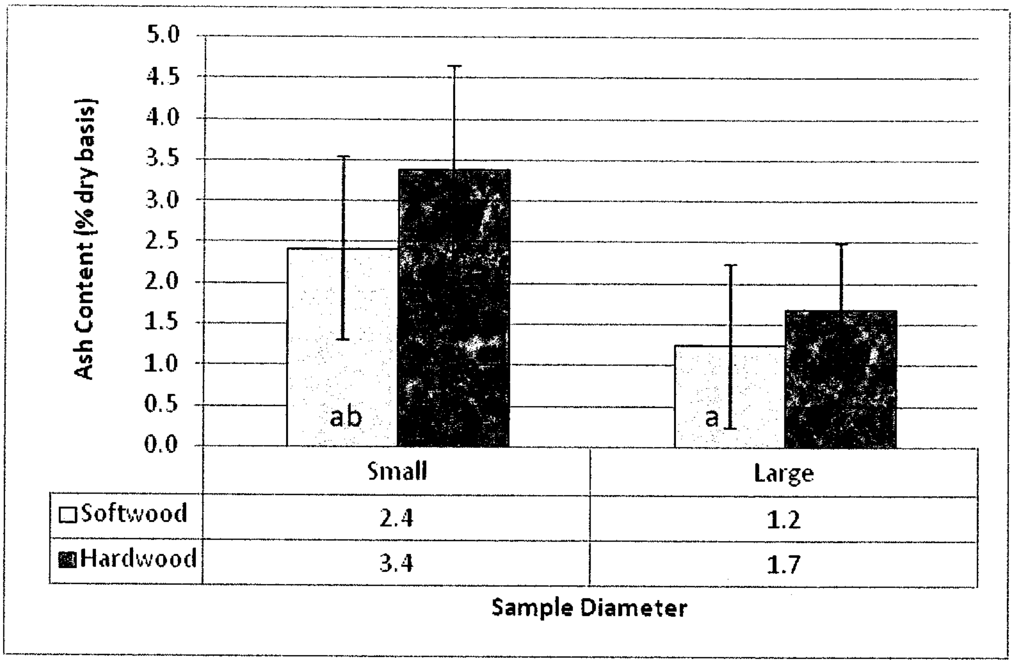


Figure 20. Average ash content of logging residue samples from cut-to-length blocks displayed against interaction of storage years and sample diameter. "Large" represent stems with diameter larger than 4 cm and "small" represents diameter equal to or less than 4 cm. Bars with no common letters are significantly different from each other. The error bars show the standard deviation.

Ash content is inversely proportional to the stem diameter as shown in Figure 19 and Figure 20. Majority of ash in a tree is concentrated in the bark tissues because of its importance to physiological functions (Bowyer *et al.* 2002). As discussed earlier, smaller diameter branches have much higher proportion of bark compared to larger branches and stems (Hakkila 1989). The ash content in barks of softwoods is reported to be approximately 2% whereas in hardwoods it averages 5%. Therefore the proportion of bark in LR is closely related to the ash content. This also explains the large difference in the ash content between softwood and hardwood in small branches compared to larger stems. In fact, our result suggests that in larger stems, softwood ash content may exceed that of hardwood (Figure 19).

CHAPTER 3 COST ANALYSIS OF PROCURING BIOMASS

3.1. INTRODUCTION

Another source of forest biomass which can potentially contribute to the energy mix is salvage biomass from wildfire burnt forest areas. Fire is a frequent and natural occurrence in the boreal forest. On average, over 10,000 ha of forest area or over 1 million m^3 of wood that is part of the harvest schedule is consumed by wildfire every year in Ontario (OMNR 2008). This results in huge losses to the forest companies, although silviculture costs to regenerate these sites in most cases can be claimed from the Ontario Forest Futures Trust. The forest companies in many cases lose their investments in roads and administration costs in spite of predetermined contingency plans. Another analysis that is imperative prior to decision making on fuel procurement is the analysis on net energy balance. Although cost analyses are sometimes carried out prior to procurement, the energy analyses are often neglected. All mechanized harvesting systems consume varying quantities of fossil fuel during procurement. Net energy balance is the ratio of energy expended for felling and extracting, processing and transporting biomass in relation to the energy obtained from biomass (Mead and Pimentel 2006; Pan *et al.* 2008). If the burnt areas could be salvaged for energy production with a high net energy balance, the losses to the forest companies could be reduced and the local economy stimulated by generating more jobs. There are a range of potential combinations of systems to process and transport the biomass. One such system, called full-tree to roadside, roadside crusher to mill (FT-CR) system is used to fell and bunch the biomass, skid it to roadside as full trees, crush it at roadside and transport it on a chip truck to the power generating station.

3.2. OBJECTIVE

The main purpose of this study was to find the economic efficiency of utilizing biomass from a case-study wildfire burnt area for bioenergy production. The specific objectives: (i) to perform cost analysis on a FT-CR system utilizing a standard costing model, and (ii) to find the net energy balance of the entire operation. First, the cost analysis of felling and extraction, processing and transporting the biomass from a wildfire burnt area of the Hogarth Plantations to the AbitibiBowater mill for bioenergy production in Thunder Bay, Ontario was conducted. The total cost of logging and transportation was also analyzed as a function of fuel price and hauling distance. Second, a linear relationship between total procurement cost and fuel prices, and hauling distances was established. Third, as part of the feasibility assessment, an energy analysis for the entire operation was carried out to assess the net energy input to output ratio. Finally, a relationship between net energy ratio and the hauling distance was established and its implications discussed.

The remainder of the chapter is organized as follows. Section 3.4 deals with theoretical models used for cost and energy estimation of the forest biomass feedstock from a wildfire burnt area using the FT-CR system. Section 3.3 describes the methodology used to collect data for use in the theoretical models. Section 3.5

presents the results, and section 5 concludes with policy implications for biomass power generation in northwestern Ontario.

3.3. MATERIALS AND METHOD

The study was conducted in the Hogarth Plantations, located to the southwest of the city of Thunder Bay, Ontario. The plantation is owned and managed by the Faculty of Forestry and the Forest Environment of Lakehead University and covers an area of 44 hectares (ha). Major species found in the area include red pine (*Pinus resinosa* Ait.), jack pine (*Pinus banksiana* Lamb.) and trembling aspen (*Populus trembuloides* Michx.). A fire burnt an area of about 15.6 ha in this plantation on April 29, 2007. The Ontario Ministry of Natural Resources attributed the cause of fire to a smoldering slash pile that was burnt in the previous winter. About 72% of the burnt area was a 35-year-old mixedwood stand and the rest was part of a 60-year-old red pine stand. Lakehead University signed a contract with AbitibiBowater Inc., to harvest the burnt 35-year-old mixedwood stand (about 11.2 ha) and utilize the crushed forest residue as fuel for electricity and steam generation at its Thunder Bay plant. The AbitibiBowater pulp and paper mill is located approximately 7 km from the plantation. Aerial photographs were taken to facilitate an assessment of the intensity of fire. Figure 21 shows the burnt area delineated on one of these aerial photographs. The intensity of the fire ranged from low to high, and from ground fire to crown fire at various locations in the stand. An inventory of the post fire stand was conducted to estimate the mass of potential hog fuel available on the site, by surveying five circular plots, each having an area of 400 m^2, for species, dbh and average tree height.

Figure 21. Aerial photograph showing 11.2 ha study area delineated.

The site was harvested using a Madill 2250B feller buncher and Caterpillar 525 wheeled skidder during November 2 to 9, 2007. A Caterpillar 325 DL with loading boom was used to feed the material into a Peterson Pacific HC 5400 grinder at roadside. The grinder was equipped with a rotor 160 cm in width, 105 cm in diameter and with 28 fixed hammers having two sided replaceable cutting bits. The 575 hp grinder had an output capacity of 86 gt$\cdot$hr^{-1}. The 150 cm x 100 cm feed throat of the grinder was continuously fed by a chain conveyer, and the crushed material was discharged at a height of 4.42 m by a 146 cm wide conveyer belt. The crushed material was directly loaded into chip vans by the grinder and hauled to the AbitibiBowater Thunder Bay mill. The weight of each load was recorded at the mill; a time study was performed on the grinder to determine the time to fill each van. The harvesting and transportation costs were estimated using cost models developed in section 3.4.3.

3.4. THEORETICAL MODEL

3.4.1. Volume and Mass Estimation

The forest biomass from the plantation was divided into three components - stem, branches and foliage. The volume, mass and energy of each component were separately estimated. The volumes of the stems for each of the three species - red pine (Pr), aspen (Po), and jack pine (Pj) - were estimated using standard volume tables illustrated by Honer (1967). Equation (11) from Schlaegel (1975) was used to estimate the total biomass in red pine and aspen stems, the oven dry mass of red pine and poplar branches was estimated, using Equation (12) from Young *et al.* (1980), and the oven dry mass of needles of red pine was estimated using equation (13) from Perala (1994).

$$M_s = e^a (D^2 \times H)^b \qquad [11]$$

$$M_b = c \times D^d \qquad [12]$$

$$M_n = 0.0007 \times D^{3.1222} \qquad [13]$$

Where,
M_s = the oven dry mass of stems in kilograms.
M_b = the oven dry mass of branches in kilograms,
M_n = the oven dry mass of needles in kilograms,
D = the diameter of the tree at breast height in centimeters,
H = the height of the tree in metres.

The coefficients, a and b, for red pine are -4.019 and 0.960 and for poplar are -

4.151 and 0.969, respectively. The coefficients, c and d, for red pine are 0.0098 and 2.5011, and for aspen are 0.011 and 2.0766, respectively.

Jack pine stem biomass was estimated using equation (14), branch biomass was estimated using equation (15) and needle biomass was estimated using equation (16), all adapted from Green and Grigal (1978).

$$M_s = 0.023 \times D^{1.72} \times H^{1.136} \tag{14}$$

$$M_b = 0.0094 \times D^{2.493} \tag{15}$$

$$M_n = 0.0471 \times D^{1.664} \tag{16}$$

Where,
M_s = the oven dry mass of stems in kilograms
M_b = the oven dry mass of branches in kilograms
M_n = the oven dry mass of needles in kilograms
D = the dbh centimetres
H = the height of the tree in meters.

3.4.2. Energy Estimation

The energy content of each component of the forest biomass was estimated using the energy calculator developed by FPInnovations FERIC Division (FERIC). The input variables in the calculator are species, component of tree, and moisture content. The moisture content of the biomass was estimated by subtracting the estimated oven dry biomass from the total mass for all loads recorded at the mill. The FERIC energy calculator displayed both higher heat value and lower heat value; only the lower heat values. Next, the amount of diesel consumed during each phase of the operation was determined and converted to total energy consumed during the operation. The heat value of total biomass was divided by this total energy consumed to determine the energy input to output ratio. The energy consumed during manufacturing of the equipments is not accounted for by the ratio.

3.4.3. Cost Estimation

The supply costs of the crushed material consist of felling, extraction, processing and transportation costs. The logging cost constitutes the operating cost of the machines and equipments; it was calculated by adding the fixed cost and the variable costs. Proportional capital cost representing depreciation of the machines and the insurance and licence cost comprises the fixed costs, whereas variable cost includes the energy, oil and lubricant, labour, and repair and maintenance costs for running the machines during the harvesting operation (Pulkki 1997) as detailed in equations (17) to (24).

$$C_o = C_c + C_e \times PMH / year + C_l \times SMH / year + C_i + C_r \qquad [17]$$

Where,
C_o = the annual operating cost
C_c = the annual capital cost
C_e = energy, oil, and lubricant cost in $\$\cdot PMH^{-1}$
C_l = the operator cost that includes all employment expenses in $\$\cdot SMH^{-1}$
C_i = the annual insurance and licence cost
C_r = the annual repair and maintenance cost

$$C_c = (P - PSV) \times \left[\frac{i}{1 - \frac{1}{(1+i)^T}} \right] + (PSV \times i) \qquad [18]$$

Where,

P = the purchase price of the machine
PSV = the present salvage value
i = the rate of interest
T = the expected useful life of the machine

$$C_i = P \times i_c + L_c \qquad [19]$$

Where
i_c = the percentage rate for insurance of purchase price
L_c = the annual licence cost.

$$C_e = (F \times F_c) + (O \times O_c) + (H \times H_c) \qquad [20]$$

Where,
F = the fuel consumption in litres(l)$\cdot$PMH^{-1}
F_c = the fuel cost in \$$\cdot$l$^{-1}\cdot$PMH^{-1}
O = the oil consumption in l$\cdot$PMH^{-1}
O_c = the oil cost in \$$\cdot$l$^{-1}\cdot$PMH^{-1}
H = the hydraulic oil consumption in l
H_c = the hydraulic oil cost in \$$\cdot$l$^{-1}\cdot$PMH^{-1}

$$C_l = w \times n \qquad [21]$$

Where,
w = the operator wage per SMH including fringe benefits
n = the number of operators

$$C_r = P \times r \qquad [22]$$

Where,
r = the percentage of purchase price for repairs and maintenance.

The transportation cost consists of the costs incurred in hauling the crushed chips from roadside to the mill in trucks, and is expressed as:

$$C_t = \frac{R \times (2T_d + T_w)}{W} \qquad [23]$$

Where,
C_t = the transportation cost in \$$\cdot$gt^{-1},
R = the hourly rate of transportation (\$$\cdot$hr^{-1}),

T_d = the time taken for transporting the material from roadside to mill in hrs,
T_w = the waiting time for loading, unloading and other unavoidable delays in hrs
W = the weight in gt·load^{-1}.

Assuming the driving time empty is equivalent to the driving time loaded. T_d is calculated using the following equation (26):

$$T_d = \frac{D_1}{S_1} + \frac{D_2}{S_2} + \ldots + \frac{D_x}{S_x} \qquad [24]$$

Where,
$D_1, D_2, \ldots, D_x$ = the distance of a particular section of a raod (km)
$S_1, S_2, .., S_x$ = the speed on that particular section of the road in km·hr^{-1}.

3.5. RESULTS AND DISCUSSION

The volume (m^3·ha^{-1}) of each of the three species - red pine (Pr), aspen (Po), and jack pine (Pj) - were estimated using standard volume tables, mass (ODt) of each of the three components of forest biomass are estimated using equations (11) to (16), and the energy estimates were estimated using the FERIC energy calculator, for each species in the wildfire burnt area. The results of estimation are presented in Table 18. The results show that red pine had the highest proportion of both volume and mass for each of the three tree components. The total biomass recorded at the mill, from the area, was 1,695 gt, and the total ODt biomass was estimated at 973 ODt using equations (11) to (16), resulting in estimated moisture content of 42.6% (GW). The 6 month period between wildfire and harvest, resulted in the drying of the dead standing trees to the lower moisture content. The net heat values, GJ·ODt^{-1}, of each component of all species were derived from the FERIC energy calculator and is presented in Table 18. Value for red pine branch was missing in the calculator; therefore, the average heat value of whole tree was used instead. The total energy estimated from the burnt area was 18,951 GJ, resulting in an average of about 19.5 GJ·ODt^{-1} of biomass. Bowyer *et al.* (2002) has outlined a procedure to calculate the net heat in GJ·gt^{-1} from the estimated value of 19.5 GJ·ODt^{-1}, using the moisture content on green basis. In accordance with the method, 19.5 GJ·ODt^{-1} is multiplied by (1 – moisture content on GW basis(42.6%)), resulting in a heat value of 11.2 GJ·gt^{-1}.

Table 18. Volume, mass, and energy estimates of the available biomass for each component

Component	Species	Volume (m^3·ha^{-1})	Total Volume (m^3)	Mass (ODt·ha^{-1})	Total Mass (ODt)	Energy (GJ·Odt^{-1})	Total Energy (GJ)
STEM	Pr	90	1,013	32	360	20.1	7,235
	Pj	62	689	24	272	18.6	5,063
	Po	25	278	9	101	18.1	1,836
BRANCHES	Pr	12	133	9	96	20.1	1,932
	Pj	8	87	6	63	20.3	1,281
	Po	1	13	1	9	18.7	174
LEAVES	Pr	5	58	4	42	20.5	857
	Pj	4	39	3	28	20.2	572
	Po	0	0	0	0	19.4	0
Total			2,311		973		18,951

The felling, extraction and processing costs of the wildfire burnt area at the Hogarth Plantation were estimated using equations (17) to (24). Standard costs for the feller buncher, grapple skidder and loader used in northwestern Ontario were input in the model. The costs for the Peterson Pacific HC5400 grinder were obtained from the dealer. The calculated fixed costs, variable costs, total costs and costs per tonne for each machine are presented in Table 19. The total cost of harvesting and processing the biomass was found to be $\$22.20\cdot\text{gt}^{-1}$, which includes contractor's profit margin of 15%. It was also found that of the total harvesting and processing cost, only 19% was attributable to the grinder. Felling was the most expensive phase costing over 36% of the total cost. A similar study by Desrochers (1998) using a smaller grinder (Maxigrind 425) found the grinding cost to be over 40% of the total estimated felling, extraction and processing cost of $\$20.63\cdot\text{ODt}^{-1}$. A lower percentage of the grinder cost found in this study can be attributed to the more efficient grinder with a larger engine having greater output per unit time. Moreover, the Maxigrind lacked a self loading conveyer belt, which reduced its overall operational efficiency.

Table 19. Production and operating costs for harvesting and processing

		Feller Buncher	Grapple Skidder	Loader	Grinder
Fixed Costs	C_c($)	108,530	80,510	106,315	121,819
	$\$\cdot\text{SMH}^{-1}$	28.03	20.79	27.46	31.46
	Insurance ($)	15,680	14,482	15,360	17,600
Variable Costs	C_e ($\$\cdot\text{PMH}^{-1}$)	26.60	21.60	16.60	76.60
	C_r ($\$\cdot\text{year}^{-1}$)	114,800	73,750	86,400	90,000
	C_l ($)	31.35	31.35	31.35	0.00
Total Cost	C_o ($)	447,955	360,395	383,465	478,557
	Hourly operating cost ($)	115.69	93.08	99.04	123.59
Production	Volume ($\text{m}^3\cdot\text{SMH}^{-1}$)	22.10	22.80	45.28	45.28
	Volume ($\text{m}^3\cdot\text{PMH}^{-1}$)	26.00	27.14	53.90	53.90
	Mass ($\text{gt}\cdot\text{SMH}^{-1}$)	16.29	16.81	33.38	33.38
Per Unit Cost	$\$\cdot\text{gt}^{-1}$	7.10	5.54	2.97	3.70
	15% contractor profit ($\$\cdot\text{gt}^{-1}$)				2.90
	Total ($\$\cdot\text{gt}^{-1}$)				22.20

In order to compare the cost estimates with Asikainen and Pulkkinen (1998), who studied three machines processing logging residue from final felling of spruce-dominated forest in Finland, the estimates were converted to 1998 Canadian dollar. The values were then converted to 2009 Canadian dollars by accounting for inflation using the Bank of Canada Inflation Calculator (BOC 2009). In their study, the machines of interest were, the Evolution 910R, a drum chipper with 360 hp output, the MOHA chipper truck, a chipper mounted on an all terrain truck bed with power output of 307 hp, and Morbark 1200 tub grinder with an engine output of 645 hp. They found that the Evolution 910 drum chipper processed approximately 55 $m^3 \cdot SMH^{-1}$ at a cost of $\$200 \cdot SMH^{-1}$ resulting in $\$3.63 \cdot m^{-3}$. The MOHA chipper processed 23 $m^3 \cdot SMH^{-1}$ at $\$120 \cdot SMH^{-1}$ resulting in $\$5.21 \cdot m^{-3}$. The Morbark 1200 grinder processed between 50-60 $m^3 \cdot SMH^{-1}$ at $\$167 \cdot SMH^{-1}$, resulting in $\$3.03 \cdot m^{-3}$. In comparison, our study found that the Peterson Pacific HC5400 grinder processed 45 $m^3 \cdot SMH^{-1}$ at $\$124 \cdot SMH^{-1}$ resulting in $\$2.75 \cdot m^{-3}$. The cost and production numbers for Peterson Pacific HC5400 grinder are, therefore, comparable to the other machines in the market.

The transportation costs were estimated using equation (23). The transportation time in moving the material from the burnt site to the mill, was estimated using equation (24) as shown in Table 20. The hauling distance consisted of 2 km of tertiary road and 5 km of paved road. The waiting time, which includes loading, unloading and unavoidable delays in the queue, was determined through time study trials in the field. The rental cost of a tractor trailer including the labour cost for the driver was \$85·hr. Since each return trip took 2.55 hours, the cost per load was calculated to be \$204, where each load carried 29.09 gt of biomass on average. Therefore, the transportation cost was estimated to be \$7.45·gt^{-1}.

Table 20. Transportation time for moving the material from burnt site to mill.

		Distance (km)	Speed (km·hr^{-1})	Time (hr)
Traveling round trip	Tertiary road	2 X 2 km	20	0.20
	Paved road	2 X 5 km	50	0.20
Delay (waiting)				2.15
Total				2.55

Combining the harvesting cost (\$22.20·gt^{-1}) and transportation cost (\$7.45·gt^{-1}) results in a total cost of \$29.65·gt^{-1} for felling, processing and transporting forest biomass from the wildfire burnt area to the mill. For the estimated energy content of 11.2 GJ·gt^{-1}, the total cost translates to approximately \$2.65·GJ^{-1}. It must, however, be noted that this cost excludes the cost of floating the equipment to the site, general administration cost, road construction cost, stumpage and other miscellaneous planning and corporate overhead costs. In this study, the transport distance was quite short but biomass harvesting can occur at a range of locations from generating station. The total cost of procurement increases significantly with the transport distance. In order to establish a causal relationship between transport distance and the total cost, a cost analysis of hauling the forest biomass from the harvesting site to mill was conducted for varying hauling distances. The assumptions for this analysis were that there is 2 km of tertiary road with an average speed of 20 km·hr^{-1}, 5 km of secondary road with an average speed of 50 km·hr^{-1}, 10 km of primary road with an average speed of 70 km·hr^{-1} and the remaining distance is highway with an average speed of 90 km·hr^{-1}. An equation (25), with total cost as the dependent variable and hauling distance as the independent variables was developed.

$$\text{Total cost } (\$\cdot gt^{-1}) = LC + \frac{R(T_w)}{W} + \frac{R\left(2\left(\frac{D_1}{S_1}+\frac{D_2}{S_2}+\dots\frac{D_x}{S_x}\right)\right)}{W} \qquad [25]$$

Where,
LC = cost of felling, skidding, processing and loading ($\$\cdot gt^{-1}$)
R = hourly rate of transportation ($\$\cdot hr^{-1}$)
T_w = the waiting time for loading, unloading and other delays (hr)
W = the weight of biomass in a truck load (gt·load^{-1})
D_1, D_2,.., D_x = the distance of a particular section of a road (km)
S_1, S_2,.., S_x = the speed on that particular section of the road (km·hr^{-1})

This equation can be used in combination with other overhead costs to determine the break-even point and profitability of a particular biomass procurement operation. The equation predicts that a similar operation located at 80 km and 100 km distance would lead to an increase in the total delivered cost, from $29.65 incurred in the study, to $34.57·gt^{-1} and $35.87·gt^{-1}, respectively.

The energy ratio was calculated by dividing the total energy available from biomass procured by the energy consumed in procuring the biomass. The results for energy consumed during felling, extraction and processing operations are presented in Table 21, and the results of energy consumed during hauling operations including floating equipment, and pick-up trucks are presented in Table 22

Table 21. Energy consumption during felling and processing

	Feller buncher	Skidder	Loader	Grinder	Total
Total (gt)	1,695	1,695	1,695	1,695	
Production (gt·PMH^{-1})	19.17	20.01	39.74	39.74	
Total PMH	88.44	84.73	42.66	42.66	
Fuel Consumption (l·PMH^{-1})	25	20	15	75	135
Total Consumption (l)	2,211	1,695	640	3,200	7,745
Energy Equivalent (GJ)	85	65	25	124	299

Table 22. Energy consumption during Hauling and by pickup trucks

	Wood hauling	Pickup Trucks	Total
Round trip (km)	14	14	
# trips	62	2 X 18	
Total (km)	868	504	
Fuel Efficiency (km·l^{-1})	2.2	5.5	
Total Consumption (l)	389.2	91.1	480.4
Energy equivalent (GJ)	15.0	3.5	18.5

It is assumed that a litre of diesel contains 0.0386 GJ of energy (Langer 2004). The total energy consumption was found to be 298.96 GJ for felling, extracting and processing operations, and 18.54 GJ for transporting, floating equipment and pick-up trucks. Therefore, in total 317.5 GJ of energy was consumed in order to procure biomass with an energy content of 18,951 GJ, resulting into an input to output ratio of 1:60. It was also found that grinding was the most energy intensive activity, consuming almost 40% of total energy expended, followed closely by felling and bunching at 30%, as shown in Table 21. Pan *et al.* (2008) found a net energy ratio range of 11.90 to 10.23, when thinning ponderosa pine (*Pinus ponderosa* P. & C. Lawson) at round trip distance ranging from 40 to 128 km. In their study, the biomass was harvested, skidded and ground using a Bandit Beast 3680 machine. The lower energy yield ratio in their study was due to longer hauling distances coupled with the fact that it was a thinning operation, resulting in a lower yield. Other studies by Keoleian and Volk (2005) reported a net energy ratio of 55.3 for agricultural production of willow biomass, and Börjesson (1996) reported a net energy ratio of 26 for logging residue after final felling with hauling distance of 50 km one way in Sweden. In order to establish a relationship between the net energy ratio and hauling distance, a sensitivity analysis was performed to generate a non-linear equation (equation 26 and Figure 22).

$$\text{Net energy ratio} = 69.79 - 9.76x + 0.61x^2 - 0.014x^3 \qquad [26]$$

Where,
x = Round trip hauling distance (km)

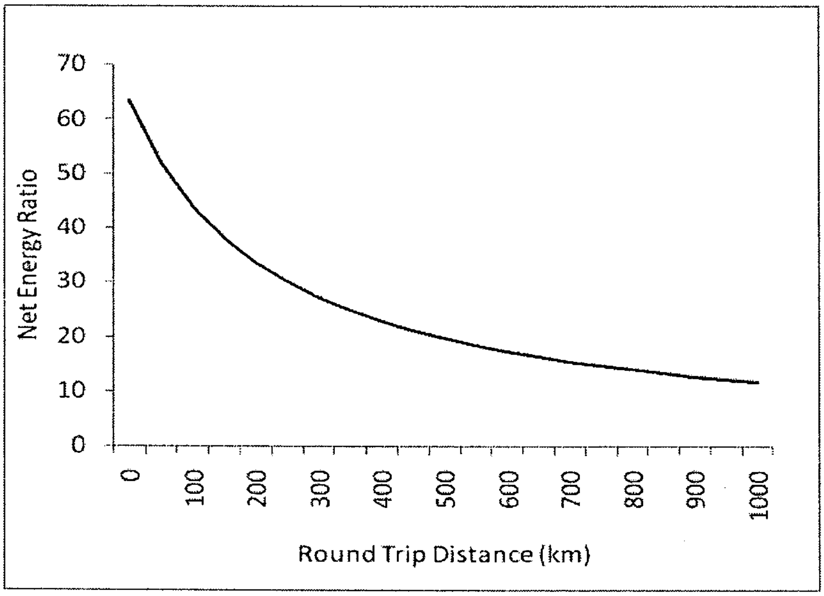


Figure 22. Sensitivity analysis of round trip distance on net energy ratio

The net energy ratio decreases exponentially and its values for 100 km, 250 km, and 500 km, were found to be 44, 30, and 20, respectively, indicating that biomass procurement becomes uneconomical swiftly as the hauling distance increases.

3.6. CONCLUSION

The cost for salvaging forest biomass from a wildfire burnt area using a full-tree to roadside, roadside crusher to mill (FTR-RCM) system was analyzed. The total cost of harvesting, processing and transportation of salvaged forest biomass from the wildfire burnt area in the Hogarth Plantations near Thunder Bay was estimated. It was found that the FTR-RCM was a feasible system for harvesting, processing, and transporting salvaged biomass from a wildfire burnt area, costing \$29.65$\cdot$gt^{-1}, with a net energy content of 11.2 GJ$\cdot$gt^{-1} at 43% MC (GW). It was also found that the transport distance significantly affects the total cost. Given the fact that this was a small scale operation and relatively small wildfire burnt area was involved, the available biomass was accurately estimated. On larger operations it takes more effort to make an accurate estimation. Since the distance between the site and the mill was relatively short in this study, the total cost of procurement was found to be low. We established an equation representing total cost as a function of fuel price and hauling distance to estimate the total cost. To assess the net energy gain, an energy analysis of the entire operation was conducted and a net energy input to output ratio of 1:60 was determined. It was found that the net energy ratio exponentially decreases with hauling distance.

CHAPTER 4 SUMMARY

The study has demonstrated that managing the storage of logging residue is much more complicated than fossil fuel such as coal. Logging residue is a low value material and extra handling costs can quickly make the feedstock uneconomical. However this study did show that the method of storage plays a large role on the quality of the logging residue and consequently the net energy yield. The study has shown that certain techniques of storing logging residue reduces the moisture content more than other methods.

Our study finds that in both FT and CTL blocks, logging residue has to be stored for at least two drying years to achieve maximum moisture reduction in the field. In this period, the cell wall polarity extenuates as a result hydroxyl groups form hydrogen bonds among themselves after moisture loss. The process has been referred to as hygroscopic ageing by Esteban *et al.* (2006).

On a species basis, the results showed hardwoods hold higher levels of moisture than softwood. There are various factors that lead to hardwoods holding higher levels of moisture than softwoods: 1) hardwoods contain a higher proportion of hemicelluloses, the most hygroscopic component of the cell wall; 2) unlike in softwoods, the pits in hardwoods do not aspirate once they reach MC below the FSP; and 3) the needles in softwood were intact for longer duration than leaves on hardwoods meaning the duration of transpiration drying in hardwoods is much shorter.

In terms of pile shape, hardwood windrow piles in all storage years displayed lower moisture content than beehive piles. The greater surface area to volume ratio in windrow piles leaves a majority of biomass exposed, allowing rapid drying. Furthermore, hardwoods due to their pronounced branching restrict compaction creating void space and low airflow resistance. Therefore hardwood piles lose and gain moisture more rapidly. However in softwood piles, windrow displayed lower MC value after year 1, but beehive piles showed the lower value after 2 years of storage. This can be attributed to the higher levels of compaction in softwood piles. The majority of logging residue in softwood beehive piles is protected from the interface with the ambient air; it takes a longer period for logging residue in these piles to reach EMC but once it is achieved, the fluctuations occur at a much slower rate compared to windrow piles.

The thermal value was not affected by storage duration but stem size and species did show significance. Stem size showed significance in both cut-to-length blocks and roadside slash piles, and species showed significance in just the roadside slash piles. Smaller diameter branches displayed higher values than larger diameter branches. Smaller diameter branches have a higher proportion of bark; bark generally has a higher thermal value than stem wood because it is richer in lignin, resin, terpenes and other combustible elements. In terms of species, softwoods displayed higher thermal value per unit mass than hardwoods due to the presence of higher percentage of lignin and resin.

Although hardwoods displayed higher MC and lower thermal value than softwoods, the higher density generally found in hardwoods make it more desirable. For example, black spruce with a MC of 25% (GW) and a thermal value of 21.2 $MJ \cdot kg^{-1}$ may seem more desirable than white birch with a MC of 30% (GW) and thermal value of 20.3 $MJ \cdot kg^{-1}$. However, taking into account the individual density for black spruce (380 $kg \cdot m^{-3}$) and white birch (480 $kg \cdot m^{-3}$), a cubic meter of black spruce will produce 6.04 kJ of heat while white birch will produce 6.82 kJ. Therefore, all qualities must be taken into consideration when evaluating biomass feedstock.

With regards to ash content, logging residue stored in slash piles did not show a significant reduction in ash content over several years of storage. Conversely, a reduction was observed in cut-to-length blocks due to rainfall leaching of the minerals. Other conclusions relating to ash content are: percentage of ash is inversely proportional to diameter, and hardwoods show higher ash content than softwoods. The actual ash content of logging residue may in fact be slightly higher than the values determined in this study. The presented values are based on samples of twigs, branches and stems; however a noticeable amount of foliage was still present, especially in softwoods. Foliage has higher ash content values than stems, branches and twigs. Also, the presence of soil contaminants in logging residues will add to the ash content. Therefore, it is important that slash be handled with the proper equipment. Handling logging residues with blades of skidders should be avoided as it may mix in contaminants from the forest floor. Driving skidders or other equipments over logging residues can result in mud from tires on logging residue.

The information presented in chapter 2 regarding storage and fuel quality should be utilized to lower the costs presented in chapter 3. There is a potential for significant cost reduction by lowering the MC of biomass feedstock. As an example, a power generating station with plant capacity of 230 MW, utilization of 45% and energy conversion efficiency of 35%, running 24 hrs a day, 350 days a year will require approximately 943,291 gt or 1,242,807 m^3 at 46% MC (GW), which, according to the costing model presented in chapter 3, will cost approximately $29.8 million. The calculation assumes the oven dry density is 410 $kg \cdot m^{-3}$ with a thermal value of 0.021 $GJ \cdot kg^{-1}$, and the volume per truck load is 50 m^3 with an average hauling distance of 80 km. Using the same assumptions, reducing the MC to 27% (GW), by storing the material for 1 year, will reduce the biomass requirement to 654,162 gt or 1,166,064 m^3 costing between $22.8 – $27.3 million, depending on productivity during processing. Further reducing the MC to 22% (GW) will reduce the biomass requirement to 605,443 gt or 1,153,226 m^3 and the cost to $21.7 – $27.0 million. Currently in northwestern Ontario, most transactions on biomass are based on green tonnes delivered. A green tonne by itself is not an accurate reflection of the energy content; the species, component and the moisture content values are required to determine the net energy produced by a certain volume of biomass. If consistent transactions on biomass is envisaged for the future, more research needs to be done to generate an accurate database of thermal values for local species and base payment on thermal value.

4.2. LIMITATIONS AND FUTURE WORK

1. Dry matter loss during the storage period was not accounted for in this thesis. The circumstance did not allow for such measurements but there have been many studies performed to predict such losses.
2. In order to gain a better understanding of the various moisture layers proposed in this thesis, piles should be excavated to the bottom rather than limited to a depth of 1.5 m. The task will be much more laborious and will require equipment to excavate the piles deeper but will reveal the moisture content profile of entire slash piles.
3. The data presented in this thesis were all collected in the summer. Feedstock quality must also be monitored in the winter before a reliable supply chain can be established. The impact of snow cover on the slash pile quality and processing methods that stave off snow have to be evaluated.
4. There are studies that show use of cover significantly improves the fuel quality. Such a study must also be established in northwestern Ontario to assess the benefits of biomass pile covering.
5. The cost benefit analysis of harvesting logging residue integrated with merchantable products, and harvesting logging residues separately from merchantable products at various intervals should be conducted, taking into account the changes in fuel quality after storage.

6. In future studies, categorization of species into general groups, softwood and hardwood, should be avoided as there is a vast difference in quality between species of each group. The classification was used in this study due to difficulty in distinguishing species in older piles.

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