FUEL CHARACTERISTICS OF NORTHWESTERN ONTARIO TREE SPECIES AND THEIR COMPONENTS

by

Steven I. Hosegood

A Master's Thesis Submitted in
Partial Fulfillment of the Requirements for the
Degree of Master of Science in Forestry

Faculty of Forestry and the Forest Environment
Lakehead University
Thunder Bay, Ontario
January 4th, 2010

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Your file Votre référence
ISBN: 978-0-494-71761-5
Our file Notre référence
ISBN: 978-0-494-71761-5

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ABSTRACT

Hosegood, S.I. 2010. Fuel characteristics of northwestern Ontario tree species and their components.

Keywords: bioenergy, calorific content, ash content, specific gravity, northwestern Ontario, moisture content, fuel characteristics, biomass.

The use of forestry residues or any biomass in the production of energy has been a topic of great discussion due to the increasing pressure to establish environmentally friendly energy production. With the current energy reform, the Ontario Government has taken an initiative to phase out coal fired generating stations by 2014. There is a plan to retrofit these plants to use biomass as feedstock to keep the power generating stations operational. At the Atikokan generating station, the focal point of this study, approximately 500,000 bone dry tonnes (BDt) of biomass would be needed to operate at 2006 operating rates (OME 2006). This study characterises northwestern Ontario tree species fuel qualities to provide information for efficient use of harvesting residues in the area.

The characterisation of thermal values has been done on seven common tree species in northwestern Ontario to create an area specific data base for use in energy production. The components of these trees which were sampled are foliage, branches, bole and bark at 10 cm diameter, and bole and bark at breast height (1.3 m). The seven species were sampled at two different sites, one 30 km west of Atikokan and the other 50 km northeast of Thunder Bay. Two sites were chosen to determine if geographic variation in thermal values exists in the different tree species, as well as to provide adequate amounts of information for a thorough database. To obtain a comprehensive understanding of fuel characteristics of the seven species and their components three different qualities were measured: 1) gross heat values; 2) specific gravity; and 3) ash content. The range of calorific values were found to be 18.07-26.80 MJ/kg. Species and component were shown to have significant effects on calorific values but sites was insignificant. The range of specific gravity was found to be 0.373-0.882. Site, Species and component were all found to have a significant effect on specific gravity. The range of ash content was found to be 0.13- 9.19%. Site, species and component were all shown to have a significant effect on ash content percentage.

Moisture content of burnt standing timber is also investigated for four species in five different fire ages. It was found that moisture content ranged from 16.81 to 53.69%. Both species and time since fire were found to have a significant effect on moisture content. Calorific content of burnt standing timber was found to have calorific content similar to living tree.

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ACKNOWLEDGEMENTS

I would like to thank all summer students hired during the summers of 2008 and 2009 for the Bioenergy project by the Faculty of Forestry and the Forest Environment. A special thanks to Michael Kukko who aided with laboratory work for my project in the fall of 2008. I would like to extend my gratitude to Brent Johnson from KBJ Logging, and Scott Booth and Gary Booth from AbitibiBowater for their help with organising the Atikokan field site. Tom Lock of AbitibiBowater played a pivotal role in the completion of my Thunder Bay site as well as the fire burnt wood study.

A huge thanks goes to my family who supported me throughout my studies, in particular my Mom, Lee Hosegood. She provided me with the most important tool that I needed, a person to vent my frustrations to. My friends, too many to name but they know who they are, gave me plenty of opportunities to take some time off school and come back fresh and for that I thank them. Throughout my study I have worked closely with Shuva Gautam, I think that I have learn more through the conversation we have shared either in our office or in Europe then any class or degree could possibly offer. I sincerely thank Pat Cybulski for his technical support as well as his wealth of experience and knowledge which he is willing to share to those who listen. Eva Scollie and LoisAnn Bender have been nothing but a pleasure for the length of my study. I will miss having the opportunity to frequent their office with yet another request that they are more then willing to help with.

I extend my gratitude to Dr. Joseph Nader for agreeing to be the external reader. His extensive knowledge of the sector and thorough review has added a great deal of value to my thesis. My committee members, Dr. Reino Pulkki and Dr. Chander Shahi have played essential roles throughout the entire process. I have learned a great deal from their open door policy and ability to relate the theoretical world to the real world. Lastly, I would like to thank my supervisor Dr. Mat Leitch for providing me the opportunity to undertake this study. He has provided stable support and guidance throughout the duration of the study. His supervising style advocates accountability on the students' part and consequently I have become a much more confident individual. I believe through the experience provided By Dr. Leitch I have become a self motivated and independant worker.

Financial support from the Ontario Centers of Excellence, AbitibiBowater and Thunder Bay Community Economic Development Commission for this research work is gratefully acknowledged.

CHAPTER 1

GENERAL INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

The use of forestry residues or any biomass in the production of energy has been a topic of great discussion due to the increasing pressure to establish environmentally friendly energy production. With the current energy reform, the Ontario Government has taken an initiative to phase out coal fired generating stations by 2014 (EPA 2007, Tang 2009). There is a plan to retrofit these plants to use biomass as feedstock to keep the power generating stations operational. If all coal burning facilities are converted to burning biomass it will be a daunting task to acquire the massive amounts needed. At the Atikokan generating station, the focal point of this study, approximately 500,000 bone dry tonnes (BDt) per year of biomass would be needed to operate at 2006 operating rates (OME 2006). Many sources of biomass are being considered to fill this demand including unutilized wood supply, mill wood waste, dedicated energy crops, fuel-grade peat, harvesting residues and wood pellets. This study characterises northwestern Ontario tree species fuel qualities to provide information for efficient use of harvesting residues in the area.

The characterisation of thermal values has been done on seven common tree species in northwestern Ontario to create an area specific data base for use in energy production. The seven tree species included in the study are black spruce (*Picea mariana* (Mill.) B.S.P.), balsam fir (*Abies balsamea* (L.) Mill), jack pine (*Pinus Banksiana* Lamb.), tamarack (*Larix Laricina* (Du Roi) K. Koch), white birch (*Betula Papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.) and black ash

(*Fraxinus Nigra* Marsh.). The seven species have abbreviations which are used at times to save space, these are Sb (black spruce), Bf (balsam fir), Pj (jack pine), Ta (tamarack), Bw (white birch), Po (trembling aspen) and Ab (black ash). There were four samples taken of each of the six tree components for all seven tree species at two sites. These components were chosen for their likelihood of being harvested for biomass: foliage, branches, bole and bark at 10 cm diameter, and bole and bark at breast height (1.3 m). The seven species were sampled at two different sites, one 30 km west of Atikokan and the other 50 km northeast of Thunder Bay. Two sites were chosen to determine if geographic variation in thermal values exists in the different tree species, as well as to provide adequate amounts of information for a thorough database. To obtain a comprehensive understanding of fuel characteristics of the seven species and their components three different qualities were measured: 1) calorific values; 2) specific gravity; and 3) ash content. Each of these three characteristics will be investigated to show differences between species and their components as well as for each component of all species. Moisture content of burnt standing timber is also investigated in Chapter 5 with details of that study contained within. Calorific value, ash content, specific gravity and moisture content have all been shown to be important factors when describing fuel quality of biomass (Hakkila 1989, Nurmi 1999, Jirjis 2005)

1.2 LITERATURE REVIEW

1.2.1 Green Energy

The use of forestry waste or any biomass in the production of energy is believed to be a promising energy source to mitigate greenhouse gases (Khan et al. 2009). The production of energy using biomass as a feedstock is looked at as "Green" or environmentally friendly (OME 2006). Green energy is in such high regard for one major reason; it is considered a carbon neutral cycle. Carbon neutral refers to the fact that burning biomass for energy releases carbon into the environment which will be reabsorbed by trees while they grow (Marland and Obersteiner 2007). This is, however, not quite perfectly carbon neutral as there are many other factors which are generally disregarded. Harvesting equipment, haul trucks and many other pieces of heavy equipment are used in the acquisition and use of biomass and all burn fossil fuels. Estimates of the carbon added by this equipment have been estimated at 3-5% (FERIC 2008), a relatively low amount but would still add to greenhouse gas emissions (Hakkila 1989).

Perhaps the most troubling part of this process is the exposure of the forest floors of the boreal forest. Forest soils have been shown to have immense amounts of stored carbon from decades of accumulated organics. These organics were not completely broken down due to cool conditions even in the summer, a low pH and the continual addition of biomass from the forest canopy (Kimmins 2004). Once the forest canopy is removed, this carbon sink is exposed to direct sunlight and can then be released into the atmosphere (Kimmins 2004). The problem with this occurring is the belief that the build up of organics takes a lot longer than getting trees back on the site, resulting in a surplus of carbon in the atmosphere from the cycle (Kimmins 2004).

There are many positives to producing green energy which more than exceed the negatives, when properly examined. One fact, which may be the most important to examine when considering green energy, is that in today's society energy is needed and will be produced whether or not it is environmentally friendly. Green energy is far less harmful to the environment than fossil fuels and releases far less SO_x, NO_x and other complex emissions common to fossil fuels (OME 2006, Marland and Obersteiner 2007, FERIC 2008). Proper site selection could further minimize possible impacts. Present day mill closures and the continuing decline of the forest industry in Canada also encourages the creation of a bio-energy sector. The creation of energy by mills will reduce energy costs and/or create a new revenue stream by selling excess green energy potentially at a premium price. There will also be job creation by developing a bioenergy sector. Hakkila (2003) estimated that the utilization of 10 million m^3 of wood residue for bioenergy production would create 11,000 new jobs in Finland.

Keeping in line with the government initiatives (EPA 2007), mills in northern Ontario have installed or are considering cogeneration facilities to reduce the cost of power at the facility and present a greener image. Green energy flows perfectly into the Ontario forestry business as mills already have harvesting equipment and there is a large amount of biomass left at roadside, which can easily be acquired. In northern Ontario the full tree and the cut-to-length harvesting systems are the most commonly used to acquire timber. FERIC (2008) found that the full tree and cut to length harvesting systems consisted of approximately 48% and 40% of all the harvesting in Eastern Canada, respectively. In the full tree harvesting system trees are cut at the stump, skidded to roadside where they are processed. During the processing large amounts of biomass are removed and left at the site in the form of tree tops, branches, foliage and bark (Pulkki 1997, Pulkki 2003). This biomass is then piled and left to be burnt in the fall (Luke et al. 1993) but could easily be ground at the site and hauled to a generating station. In the cut-to-length harvesting system, trees are felled in the forest stand where they are processed into various wood assortments. Since the felled trees are processed at the stump the tree tops, branches, foliage and bark are scattered throughout the cutover (Pulkki 1997). The distribution of logging residues makes the acquisition of biomass in this harvesting system more difficult but can still be accomplished in an efficient manner.

Combined heat and power (CHP) is the creation of energy and steam, although similar in most regards to other power plants, the steam is used rather than treated as a waste product (Uddin and Barreto 2006). Currently many forest product mills have CHP plants or a biomass boiler for steam generation to which a turbine for generating electricity could be installed. With most of the needed infrastructure in place, the next step is to begin creating energy using CHP technology. When CHP facilities are coupled with mills or other users of the steam produced, up to 89% of the energy released by the feedstock is captured (Uddin and Barreto 2006).

1.2.2 Calorific Values

The calorific value of trees and their components is important information in the establishment of a bio-energy sector in Ontario and as the operations are further refined. The calorific value in this document refers to the heat released when all of the given substance is combusted (Kryla 1984). Calorific values can be reported in a variety of ways depending on the circumstances, but is usually reported as energy per mass.

Throughout this document calorific values will be reported as mega joules per kilogram (MJ/kg) which is the accepted format in the current literature. This information can allow increases in efficiency in the entire biomass utilization system from proper sorting of materials through to boiler operations at the power plant. A local database for forestry waste products is necessary due to trees having a high potential for variation in their thermal values. This variation is potentially caused by factors such as site characteristics, species and tree component (Singh and Kostecky 1986, Nurmi 1993).

1.2.2.1 Site Characteristics

Site characteristics play an important role in fuel characteristics of trees in northwestern Ontario as trees are very much a product of their environment. Crucial site characteristics such as climate, soils, drainage, forest type and competition are all important factors which influence the growth rate of a tree (Panshin and DeZeeuw 1980, Wilson 1984). Growth rate is an extremely pivotal factor in the calorific value of a tree's wood as it will affect the wood type, cell wall thickness and therefore chemical makeup.

There are two major types of wood which are classified botanically as either softwood or hardwood. In temperate areas, where there is a definitive growing season the formation of annual growth rings occur leading to the development of earlywood and latewood (Simpson 1999). Earlywood is produced in the spring once cambial activity resumes and has larger cells with lower density to aid in the conductivity of water. Latewood is formed in the last part of the growing season and has a higher density to increase rigidity and support the tree (Panshin and DeZeeuw 1980, Simpson 1999). Fast growing trees require more water and will therefore have a larger earlywood band than slower growing trees. As growth rate decreases the amount of earlywood becomes closer to that of latewood which is far less variable than the earlywood band (Panshin and DeZeeuw 1980). Changes in the earlywood to latewood ratio will affect the calorific value of wood mainly due to cell wall components of the two different wood bands (Panshin and DeZeeuw 1980). Latewood has much thicker cell walls and therefore, higher amounts of lignin than earlywood due to a thicker secondary wall structure (Panshin and DeZeeuw 1980). With different proportions of cell wall components, most importantly additional lignin, it will cause the earlywood and latewood to have different gross calorific values.

Lignin is the most pivotal cell wall component in determining the calorific value, as lignin has been shown to have much higher energy content than cellulose and hemicellulose (Rhen 2004). Hemicellulose and cellulose have much lower and similar calorific values which are overviewed in greater detail in section 1.2.2.2. This fact could cause the calorific values in northern Ontario to be far higher than reported in many of the southern sources. Having higher calorific values could allow far more energy to be produced from available biomass sources. The need for increased knowledge of calorific values of Canadian tree species and their components is recommended by Kryla (1984).

Another site characteristic which could cause a change in energy values is geographic location. Nurmi (1993) found that sites located in northern Finland produced significantly higher calorific values than sites located 500 km to the south. In addition to the shortened growing season in the north, tree evolution could also have an influence on calorific values. Slight differences in the genetics as well as the different phenotypical expression of the genes caused by climate and site could have large implications to the formation of wood and its resulting calorific values (Russell 2002). With enough characterisation of fuel quality in northern Ontario, zones could be set up with similar heating values to enable more accuracy in energy estimates. This concept would be similar to seed zones for trees which have been extremely effective in promoting replanting trees based on their geographic location (Parker 1992, Russell 2002).

1.2.2.2 Tree Species

Tree species has perhaps the most profound effect on the calorific value of trees dictating the overall characteristics on the tree. The most apparent difference in northwestern Ontario is if the tree species falls into either hardwood or softwoods.

Hardwood trees are aptly named due to their containing wood that is normally harder and denser than softwoods. Hardwood and softwood trees have many physiological differences which could potentially affect the calorific values of the two broad categories (Simpson 1999). There are three major components of wood; cellulose, hemicellulose and lignin make up to 99% of the total dry weight of both hardwoods and softwoods with the remaining few percent being made up of extractives (Jane 1956). Cellulose is a homopolysaccharide made up of glucose molecules and is the central structural element in the cell walls in trees. Hemicelluloses are highly branched heteropolysaccharides and consist of sugars such as galactose, xylose and mannose, as well as glucose (Rhen 2004). Lignin is a three-dimensional polymer of phenylpropane units (Rhen 2004) that contributes to the mechanical characteristics of wood giving it both compressive and tensile strength, as well as rigidity (Raven 1999). In hardwoods and softwoods the percentage of these components are slightly different: hardwoods are approximately 50% cellulose, 26% hemicellulose and 24% lignin; and softwoods are approximately 50% cellulose, 23% hemicellulose and 27% lignin (Jane 1956). Panshin and DeZeeuw (1980), reported that the chemical composition of North American trees can be summarized as cellulose, 40% to 50%, hemicelluloses 20% to 35%, lignin 15% to 35%, and with the remaining fraction consisting of ash, resins, tannins and various other components which make up a few percent at most. Although this is a general trend for all wood, softwoods lignin content is at the higher end of the scale and hemicelluloses at the low end of the scale; for hardwoods the opposite holds true.

The importance of these different compositions is that each component has its own calorific value and slight differences could drastically affect the calorific value of wood. Of all the wood components, extractives are found to have the highest calorific value: 32.3 MJ/kg (Chandler 1983), 34.9-37.2 MJ/kg (Howard 1973), and 38.9 MJ/kg (White and Plaskett 1981). Lignin has been found to have a gross calorific value between 23.3-25.6 MJ/kg (Baker 1983) and 26.7 MJ/kg (Tillman 1978). Hemicellulose was found to have a calorific value between 17.5 MJ/kg (Tillman 1978) and 18.6 MJ/kg (Baker 1983), while that of cellulose is 18.7-19.5 MJ/kg (Tillman 1978). The numbers reported for each component do have variability but this can be explained by use of different extraction methods as well as laboratory equipment (Jane 1956). Although there is some discrepancy between different published data, lignin has a higher calorific value than the other two wood components. Softwoods could be expected to have a higher calorific value due to having lower amounts of hemicelluloses and higher amounts of lignin. This trend may not hold true for all species of softwoods as each species will have a unique ratio.

1.2.2.3 Tree Components

Tree component is also an important factor to consider when describing fuel characteristics of trees. Although wood is the most abundant material present in trees it may not have such a dominant part in the use of forest residues, as the bole of the tree is used in lumber and paper products. The remaining biomass will consist of branches, foliage, tree tops and bark.

1.2.2.3.1 Bark.

Bark may end up playing one of the most important roles in sustaining the emerging bioenergy sector as wood can be used for many timber products which can be very profitable. Bark is a much more variable substance as every tree species will have differences in the way bark is grown. Smooth barked trees such as birch form a ring periderm to produce the bark. Other species, such as pines, produce periderms, which are not continuous and produce bark which quickly cracks on the outer layers (Jane 1956). Bark is also composed of different types of phloem cells to create the dead outermost layers of bark. Many bark types use cells which are lignified, thus increasing the calorific potential. However, just as many species use unlignified cells (Panshin and DeZeeuw 1980), bark can also contain extractives (e.g. the bark of balsam fir), which could drastically change the calorific value of the bark. With so many variables in bark, it is difficult to form accurate predictions of calorific values. This uncertainty makes it that much more important to better define the calorific value of bark by species.

1.2.2.3.2 Foliage.

Foliage perhaps is the most varying component of trees due to their composition being so specific to species, location in crown and time of year. For example, conifers load sugars and resins into the needles to allow survival over winter and would increase the calorific value (Wilson 1984). Broad leaves are not present on trees in the winter months in temperate areas and in the summer, the composition will change depending on the development and crown position of leaves (Raven 1999). Nutrients in the foliage will change between species but more drastic changes will be present between hardwoods and softwoods. Softwood needles are higher in cellulose and hemicelluloses, lowering the calorific value, while hardwood foliage has higher lignin values and lower amounts of carbohydrates (Nurmi 1993).

1.2.2.4 Previously Published Calorific Data

There is a large amount of published data on gross heating values of trees (Table 1), but there are many limitations of this data. Singh and Kostecky (1986) report calorific means which range from 19.122 to 21.099 MJ/kg for softwoods and 18.396 to 20.091 for hardwoods which were sampled in Manitoba and summarized in Table 1. Although this study was very thorough, it did not include very specific geographic information on study sites nor was that even taken into consideration as suggested by Nurmi (1993). Kryla (1984) found that for tree species native to Canada, the mean calorific value for softwoods is 21.18 MJ/kg and for hardwoods 19.35 MJ/kg. The study completed by Kryla (1984) was extensive and thorough but contained limited information on certain trees and no information on black ash. There was little consideration to where the components were sampled in the trees; the only information provided was if it was wood, bark, branches or foliage. It was also indicated that many of the studies which were used to compile this database used non-experimental calorific values or were from sources outside of Canada. Ince (1979) was useful for supplementing information on bark but most of the information provided was derived chemically and not experimentally. A lack of information existed when it came to sampling and testing procedure in Ince (1979) and Kryla (1984). There was also no sampling at different heights along the stem which completely disregarded the potential differences.

Table 1. Previously published data on tree species and components of this study.

Tree Species	Tree components gross heating value in MJ/kg			
	Bole	Bark	Branches	Foliage
Black spruce	18.784[a]	19.478[a]	20.679[a]	20.873[a]
		21.27[b]	21.46[b]	20.62[b]
		19.18[b]		
		20.03[b]		
		21.266[c]		
		20.026[c]		
		20.426[c]		
Balsam fir	18.746[a]	18.527[a]	20.57[a]	21.504[a]
	20.04[b]	21.72[b]	21.10[b]	20.93[b]
	19.9[b]	20.61[b]		23[b]
		21.722[c]		21.19[b]
		21.95[c]		
Jack pine	19.443[a]	21.299[a]	21.374[a]	21.43[a]
	20.15[b]	21.3[b]	21.95[b]	
	19.4[b]	21.84[b]		
		21.85[b]		
		20.21[b]		
		20.77[b]		
		20.38[b]		
		21.848[c]		
		20.771[c]		
		21.722[c]		
Tamarack	19.783[a]	19.49[a]	21.463[a]	20.089[a]
		20.96[b]		19.41[b]
		20.957[b]		
White birch	18.527[a]	20.23[a]	19.721[a]	21.119[a]
	18.82[b]	24.09[b]	21.11[b]	21.93[b]
	20.81[b]	21.94[b]		
		23.98[c]		
		22.997[c]		
		24.032[c]		
		23.981[c]		
Trembling aspen	18.669[a]	19.509[a]	19.905[a]	18.804[a]
	20.71[b]	20.26[b]	20.83[b]	22.65[b]
	19.35[b]	19.62[b]	20.36[b]	22.44[b]
		20.264[c]		21.65[b]
		20.694[c]		21.08[b]
				19.76[b]
				21.16[b]

[a] indicates source of information is Singh and Kostecky (1986)
[b] indicates source of information is Kryla (1984)
[c] indicates source of information is Ince (1979)

1.2.3 Ash Content

Ash content is the total weight of non-combustibles or inorganics in material being burnt. Ash content is an important fuel characteristic due to its relationship with the gross calorific value of biomass, with the more non-combustibles in biomass the lower the gross calorific value (Hakkila 1989, Rhen 2004). The gross calorific value is affected by non-combustibles in biomass because it simply reduces the amount of combustible material thus reducing the amount of available energy which can be stored and released during combustion (Monti et al. 2008). It has been shown that gross calorific value is negatively related to ash content; for every 1% increase in ash content the heating value decreases by 0.2 MJ/kg (Cassida et al. 2005). The ash properties of trees depend on many factors such as species, component, soil type, climate conditions, storage and collection, making available sources exceptionally variable when available (Hakkila 1989, Demeyer et al. 2001).

There is limited literature on the ash content of Canadian tree species and none on their specific components. Hakkila (1989) reports ash content of 0.9-1.6% for full trees of five Finnish tree species. Wood has consistent and low ash content; stem wood ash content in the United States for softwoods and hardwoods were reported to be 0.3±0.1% and 0.5±0.3%, respectively (Hakkila 1989). Branch wood can be slightly higher in ash content and is much more variable than stem wood due to the content of reaction wood. Ash content in the bark component can fluctuate greatly between tree species and has been found as high as 16.42% (Celtis sp.)(Hakkila 1989). Five Finnish species were found to have an average of 2.97% ash in stem bark and 4.97% average in their foliage (Hakkila 1989).

Ash from trees consists mainly of calcium, potassium, magnesium, silicon and manganese, which usually account for 70% of the ash present (Panshin and DeZeeuw 1980). It has been identified that calcite ($CaCO_3$) is the major component of tree ash and therefore calcium is the most abundant mineral to cause ash formation (Etiegni and Campbell 1991). Calcium is a major component of living cells as it is used for many physiological functions. Cells such as parenchyma are living throughout trees and will have calcium in the cytoplasm of the cell which will remain after the cell dies. There are certain classes of trees, which will have higher amounts of parenchyma due to their cellular make up. Ring porous hardwoods (e.g., black ash) have more parenchyma cells resulting in higher ash content than diffuse porous woods or softwoods which contain little parenchyma in wood (Panshin and DeZeeuw 1980).

Ash content can also have detrimental effects to the boiler system and reduce its efficiency. The higher amount of inorganics in biomass allows greater amounts of residue on burning equipment (Monti et al. 2008). Ash must also be removed from the boiler to avoid congestion inside the burning chamber; extraction systems are designed only to handle certain amounts of ash and exceeding that will cause accumulation of ash (FERIC 2008). Ash is not solely an unwanted by-product and there is currently research being done to use biomass ash in a productive manner. When policies allow it, wood ash can be used as a fertilizer to replenish nutrients at the site (Demeyer et al. 2001).

1.2.4 Specific Gravity

Specific gravity (SG) is a ratio measurement (equation 1) and expresses the density of any substance as it compares to water at 20°C which has a specific gravity equal to 1.0 (Comstock 1984). Although this ratio is expressed without units it is equal to density expressed as g/cm^3.

$$SG = \frac{OD \quad weight}{Weight \quad of \quad displaced \quad volume \quad of \quad water} \qquad [1]$$

Equation (1) requires that the numerator is always the OD weight of the substance and the denominator is the weight of the displaced volume of water. It is important to report the moisture content of the sample used for displacing the water as there are dimensional changes that occur to fibres below the saturation point (Panshin and DeZeeuw 1980). As the moisture content decreases, the total volume of the sample will decrease making the ratio in the equation smaller and the specific gravity larger. Therefore, the moisture content plays an important role in woody substances when determining specific gravity and the highest results will be reported when samples are oven dry and lowest when samples are green (Panshin and DeZeeuw 1980).

There are many factors which can be attributed to the specific gravity of different components of a tree especially its wood. Growth rate, tree species, environment, component and age of the tree are all important influences on the specific gravity. These factors influence wood in a predictable manner and manifest themselves in the specific gravity. The major factors in specific gravity in the wood are the cell wall thickness and cell size; the thicker the cell walls and the less air space, the higher the specific gravity (Panshin and DeZeeuw 1980). These differences occur throughout the tree both horizontally and vertically depending on the wood type. Horizontally differences are found in each growth ring in early and latewood, and from pith to bark differences are found between mature and juvenile wood. Mature wood is denser than juvenile wood in two regards: thicker cell walls and less conducting tissue therefore less air space (Panshin and DeZeeuw 1980).

There is an abundance of published sources on the specific gravity of wood and for every tree species in this study (Table 2). Unfortunately, there is a large information gap in published specific gravities on other components of trees such as bark, branches and foliage. Published data of specific gravities is also mainly from United States sources and due to slower growing conditions in northern Ontario there could be higher densities.

Table 2. Previously published specific gravities of tree species in northwestern Ontario.

Tree Species	Specific Gravity of wood	
Black spruce	0.42[a]	0.42[b]
Balsam fir	0.35[a]	0.36[b]
Jack pine	0.40[a]	0.38[b]
Tamarack	0.53[a]	0.53[b]
White birch	0.55[a]	0.55[b]
Trembling aspen	0.38[a]	0.38[b]
Black ash	0.49[a]	0.49[b]

[a] indicates source of information is USDA (1987)
[b] indicates source of information is Hoadley (1990)
[b] also indicates volume is at 12% moisture content

1.2.5 Effects of Moisture Content

The moisture content of biomass plays a crucial role in determining the fuel quality and characteristics of potential feedstock. Although it is extremely important the effects of water will only be reviewed by this study as the effects of water are well documented. Water is a fire retardant and must be removed from biomass before full combustion can take place. During combustion water is vaporized from the feedstock, and the heating and change of state of water takes heat from the feedstock's exothermic reaction (Hakkila 1989). If all of the feedstock is burnt then this would not affect the total energy released but it does affect the ability to capture heat in flue gases using current boiler systems (Ince 1979). In a closed system, all of the energy of the produced steam could be recaptured but in boilers there is the opportunity for the steam to escape with some heat of the reaction. In any heat recovery system it is unavoidable that some heat will escape through flue gases but the amount can be extremely variable (Hakkila 1989). The amount of heat discharged through flue gases is dependent on design of the system, method and skill of the operator, and fuel quality (Ince 1979).

Usually the moisture content of biomass feedstock is reported on a wet weight basis which is essentially the percentage of weight that is water and the remainder is biomass. For example, if 1 kg of wood is entering the boiler at 45% moisture content then the wood weight is 550 g and water weight is 450 g (Ince 1979). Moisture content affects the total recoverable energy in a heat recovery boiler as all moisture content escapes as water vapour in flue gases. When there is no moisture content in biomass, the available energy is known as the higher heating value. The available potential heat of wet biomass can be calculated using equation 2 (Ince 1979).

$$Available\ \ Potential\ \ Heat = (1 - MC_{WB}) \bullet HHV \qquad [2]$$

Where,

MC_{WB} is the moisture content on the wet weight basis in a decimal fraction.

HHV is the higher heating value of the substance in MJ/kg.

There are also additional factors which can influence the recoverable heat energy such as quantity of excess air admitted into the furnace, temperature of stack gasses, amount of thermal radiation, mineral build up on heat exchangers and hydrogen content of the fuel (Monti et al. 2008). Most of these factors are to do with boiler operation and maintenance, but hydrogen content is important to consider for biomass. Wood and bark contain approximately 6% hydrogen by dry weight which will produce water with combusting oxygen and vaporize and release with flue gases (Ince 1979).

CHAPTER 2

CALORIFIC VALUES

2.1 INTRODUCTION

The calorific value of biomass is extremely variable and even within a specific group of plants can vary significantly (Monti et al. 2008). Different tree species may have extremely different calorific content, but even within a single tree the different components of the tree could produce drastically different values (Singh and Kostecky 1986).

The objectives of this chapter are to examine the calorific value of biomass and understand some of the factors which affect it. Experimental objectives include: 1) testing if different calorific values exist between the two areas of the study; 2) if there are differences between species; and 3) if there are differences between components of a tree. Similar tree species and components will be grouped into subsets to reveal similarities within different treatments. The creation of a database of calorific values for northwestern Ontario tree species and their components will further the development of the bioenergy sector in the area.

2.2 METHODOLOGY

2.2.1 Study Area

To ensure a representative fuel description of the wood supply to northwestern Ontario two sites were chosen. The first was located 30 km west of Atikokan at the coordinates 48.84°N 91.96°W (Figure 1) in the Crossroutes Forest and was selected to provide information for that area due to its proximity to the Atikokan power generation station. The second site is located 50 km northwest of Thunder Bay and approximately 220 km east of the Atikokan site, at the coordinates 48.79°N 89.03°W (Figure 2) in the Black Sturgeon Forest and was selected to provide information for the Thunder Bay area as well as explore the potential for geographic variation as shown by Nurmi (1994). These sites are also located strategically to enhance studies by FERIC and other Lakehead University researchers who are investigating the logistics of biomass harvesting. Fuel quality information provided to these parallel studies will further increase the utility of the findings from this thesis. Both study sites include two locations due to the availability of all seven tree species at both sites. At the Atikokan main study site, the northern green dot (Figure 1), black ash and tamarack were not present and were collected 5 km to the south. At the Thunder Bay Site, all species but black ash were present at the main study site (southern green dot Figure 2) and black ash was collected 30 km to the northwest.

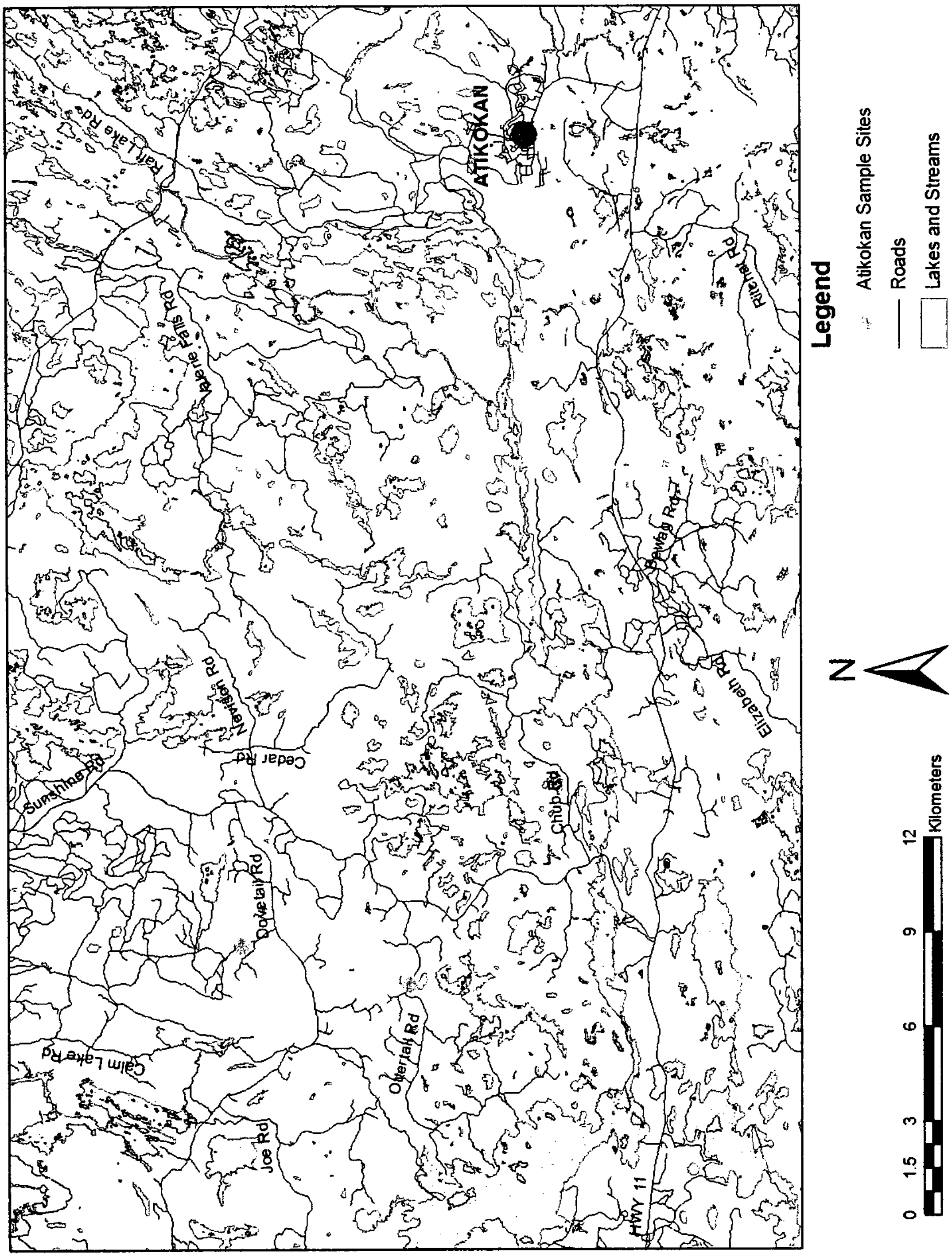


Figure 1. Field sample sites for the Atikokan Area.

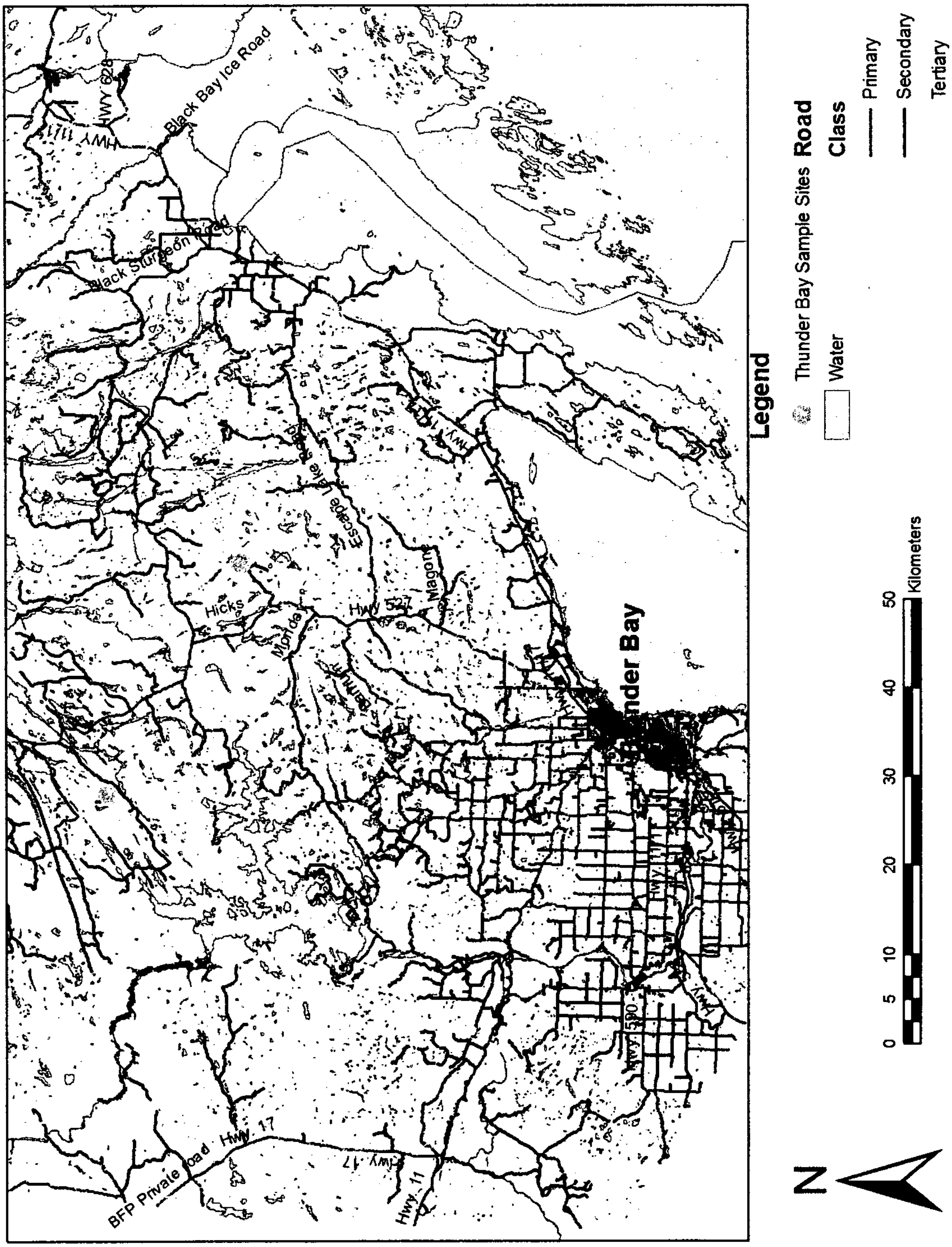


Figure 2. Field sample sites for the Thunder Bay Area.

The sites themselves were of harvestable size and age and were either in the process of being harvested or had already been harvested. The sampling procedures at each site were as similar as possible considering operational constraints enforced by Abitibi-Bowater. In the Crossroutes Forest, workers are not permitted to operate chainsaws for the purposes of felling trees and it was insisted that all collections were done out of skid piles at roadside. The trees at the site in the Black Sturgeon Forest were selected by field crews and cut by chainsaws.

2.2.2 Field Sampling

2.2.2.1 Tree Species

There were seven tree species at each site, selected because of their potential importance to the bioenergy sector: jack pine, black spruce, balsam fir, tamarack, white birch, trembling aspen and black ash. Jack pine, black spruce, balsam fir, white birch and trembling aspen are of the five most intensively harvested species in Ontario making up over 92% of the total volume of wood harvested in Ontario in 2004/2005 and over 80% of the area (OMNR 2008). These species were chosen due to their abundance in Ontario's forest and the high likelihood that forestry biomass will come from these five species. The remaining two species, tamarack and black ash were chosen because of their reputation of having exceptionally high calorific content and some of the highest wood densities of the species present in the area (Table 2). From these seven different tree species six components were collected from each of the four trees per site.

2.2.2.2 Tree Components

The six components include bole wood and bark at breast height, bole wood and bark at 10 cm diameter, branches less than 5 cm in diameter and foliage (Figure 3). Each of these components were chosen to complement the most likely available forest biomass and compare with previously published literature, where available. Bole wood and bark at breast height was chosen to represent the commercially viable part of the tree which may be used in the form of bark and chips from sawmills and rejected pulp chips. The bole wood and bark at 10 cm diameter was chosen to represent the tops of the tree left in slash piles after topping the tree. Most mills do not accept logs smaller than 10 cm in diameter Abitibi-Bowater's field handbook indicates a minimum top diameter of 10 cm (Abitibi-Bowater 2008). The bolt sampled at the top of the tree represents the potential differences between the upper and lower parts of the tree's wood and bark. Branches less than 5 cm diameter are to represent the branches left after delimbing trees.

Figure 3. All components of a black spruce tree air drying. Source: Hosegood 2008

2.2.2.3 Tree Selection Techniques

In the field, two tree selection techniques were employed due to operational limitations imposed by Abitibi-Bowater to ensure safety to field staff. The two techniques achieved the same sampling goals to ensure comparable results. Both techniques sample trees randomly, which are of merchantable size, sample all six components from the same tree and sample components from the same locations or randomly as appropriate.

2.2.2.3.2 Fell and Skid.

The first technique involves the selection of trees, which were felled and skidded to roadside by heavy equipment and was used for 20 of the 56 trees. The 20 trees which were selected in this fashion were the four trees of black spruce, jack pine, balsam fir, white birch and trembling aspen at the Atikokan site. The first selection criteria of trees being randomly selected and of merchantable size are already satisfied from the machine operator randomly selecting trees for the study and only cutting merchantable sized trees. The four trees of each species were skidded out and laid to the side of the trees being skidded out by the harvesting operation. A few of the species had only four trees cut at the site due to them not being of interest for the harvesting operation. When there was more than four trees to choose from, the safest most accessible trees were always chosen to limit potential injury to field workers. Ensuring consistent sampling of components was more of a challenge when trees were felled by machinery and the field crew did not have access to the tree where it was standing. The wood and bark component at breast height was the most difficult problem to overcome as the 1.3 m was not marked while the tree was standing. The solution was to take the acceptable stump height of 20-40 cm (Abitibi-Bowater 2008) and assume the average of 30 cm was left at the stump for every tree (Figure 4). Each sample bolt was cut from the tree using chainsaws 1 m above the butt of the tree giving the desired 1.3 m sample point. Extra caution was also used when sampling branches and foliage as it was difficult at times to determine which tree, of trees piles together, each branch was from. Branches and leaves were randomly selected from the entire length of the tree with the only limitation being that the branch must not be greater than 5 cm in diameter. Using a diameter tape the bolt to be cut to represent the bark and bole at the 10 cm diameter was identified. Identifying the appropriate bolt was not as challenging as branches but it was done to ensure that each bolt cut was matched to the appropriate sample tree.

Figure 4. Field sampling of balsam fir which were cut and skidded to road side. Source: Hosegood 2008

To ensure that the entire sample tree stayed together as an identified sample set, the lower bole section was identified using a metal tag and placed in a large nylon bag with all of the other components. The bag itself was then identified using a large black marker. Each component was placed in the large nylon bag with the exception of the foliar sample which was first placed in a labelled paper bag to keep the sample material from getting lost or contaminated. The nylon bags were then sealed and brought back to the laboratory as soon as field sampling was completed.

2.2.2.3.2 Standing Trees.

The second selection method, sampling from standing trees in forest stands, was the originally intended way to sample and was done for the remaining 36 trees. All trees from the Thunder Bay Site and the black ash and tamarack from the Atikokan site were harvested using this method. The selection of the trees was done randomly and the tree was checked if it was of merchantable diameter, defined as greater than 10 cm outside bark (OMNR 2007). Four trees were selected for each species with a diameter at breast height outside bark (DBH) at least in the 10 cm class. Breast height was marked using spray paint and then the tree was felled (Figure 5). Each component was then sampled from the tree in the same fashion as previously outlined. All samples were labelled at the time of harvest using the same methods as described above.

Figure 5. Field sampling of jack pine which was standing in a forest stand. Source: Hosegood 2008

2.2.3 Sample Preparation

The following section is adapted from the manual of laboratory procedures prepared by the Lakehead University Wood Science and Testing Facility for sample preparation for use in the Parr 6200 bomb calorimeter (LUWSTF 2008). Depending on the type of samples arriving at the laboratory the most efficient way of processing was chosen. For ease of processing the samples were first dried to 10-20% moisture content before beginning the break down of samples. This was accomplished by removing the samples from the nylon bags and spreading them out on tables to air dry (Figure 3). For stem wood the following procedures were used:

1) Bark was tested separately and was removed while the sample was still wet. It peeled off easily at the inner bark layer using a large flat head screw driver. This also allowed the log to dry more rapidly than with the bark on.
2) The sample of bole wood being broken down was held firmly in a collection basin. Holes were drilled along the length of the sample using a spade drill bit. This technique produces shavings which are suitable for the large Wiley mill and are also representative of the wood from bark to pith. No holes were within 2.5 cm of the ends of the bolt to avoid the area of the log that is contaminated by dirt or more importantly oil from the chainsaw. This technique was continued until approximately 100 g of material was collected from each sample.
3) The material produced was put in a labelled paper bag and placed in the drying oven. After allowing 24-48 hours for samples to dry at 70°C the shavings were run through the large Wiley Mill without building up excess residue. Before samples are run, the large Wiley mill is cleaned using compressed air or the shop vacuum to limit cross contamination as much as possible. When material could not be removed by either of these methods the material was scraped off using various tools.
4) Once the sample was ground it was reground through the mini Wiley Mill (Figure 6). To ensure a complete burn through the calorimeter no less than 40 mesh was used resulting in a particle size no greater than 0.422 mm. The sample was ground until a labelled specimen container was filled. These air tight containers preserved the sample until it is run through the calorimeter. The mini Wiley Mill is cleaned in the same fashion as the large mill before each sample is ground.

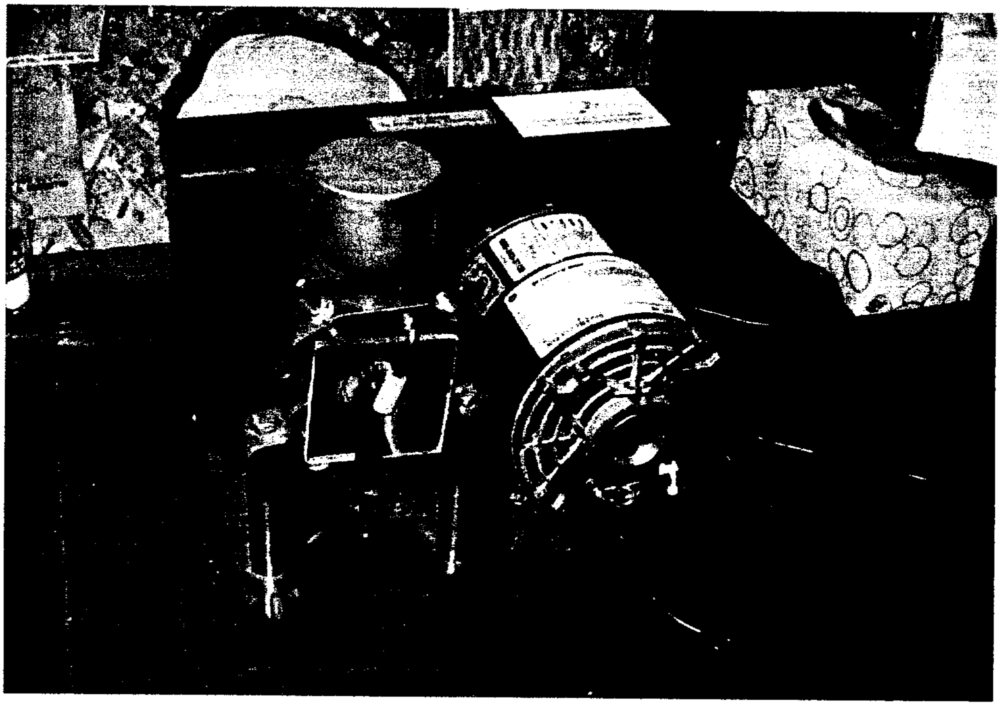


Figure 6. Mini Wiley Mill used to grind samples to 40 mesh size. Source: Hosegood 2008

For branches the following procedure was used:

1) The branches were run as bark and wood combined as one component. Branches that were too large to break down using pruning shears required the use of a drill and drill bits to produce shaving for the large Wiley Mill. Either method used will produce sample material which has appropriate amounts of wood and bark.
2) Follow the procedures for roundwood (steps 3-4) to finish the grinding process for branches.

For foliage the following procedure was used:

1) Needles and leaves were inspected and wood, bark and branches were removed to have a pure foliage sample.

2) Follow the procedures for roundwood (steps 3-4) to finish the grinding process for foliage.

For bark the following procedure was used:

1) Bark was run separately from the bole wood and was initially broken down using hand held pruning shears or by hand. The bark which was within 2.5 cm of the end of the bolt was not used due to potential contamination of chainsaw oils.
2) Follow the procedures for roundwood (steps 3-4) to finish the grinding process for bark.

2.2.4 Determination of Calorific Values

Using a Parr 6200 Oxygen bomb Calorimeter (Figure 7) and Parr 6510 water handling system (Figure 7) all calorific values were determined as outlined in the Parr Operating Instruction Manual which was adapted from numerous ASTM standards (Parr 2007).

The Parr 6200 Oxygen bomb Calorimeter has many features to minimize errors. The bomb and bucket combinations used in the calorimetry process are standardized using benzoic acid tablets of known calorific values. The calorimeter also has a calorimeter jacket which surrounds the bucket and acts as a thermal shield. This jacket is kept at 30±0.5°C and is used to minimize the effects of drafts, radiant heat, changes in room temperature and any other environmental conditions which may change during a test. However the jacket does not prevent all heat leakage from the system but does reduce it significantly and also keeps the potential heat loss uniform across all tests.

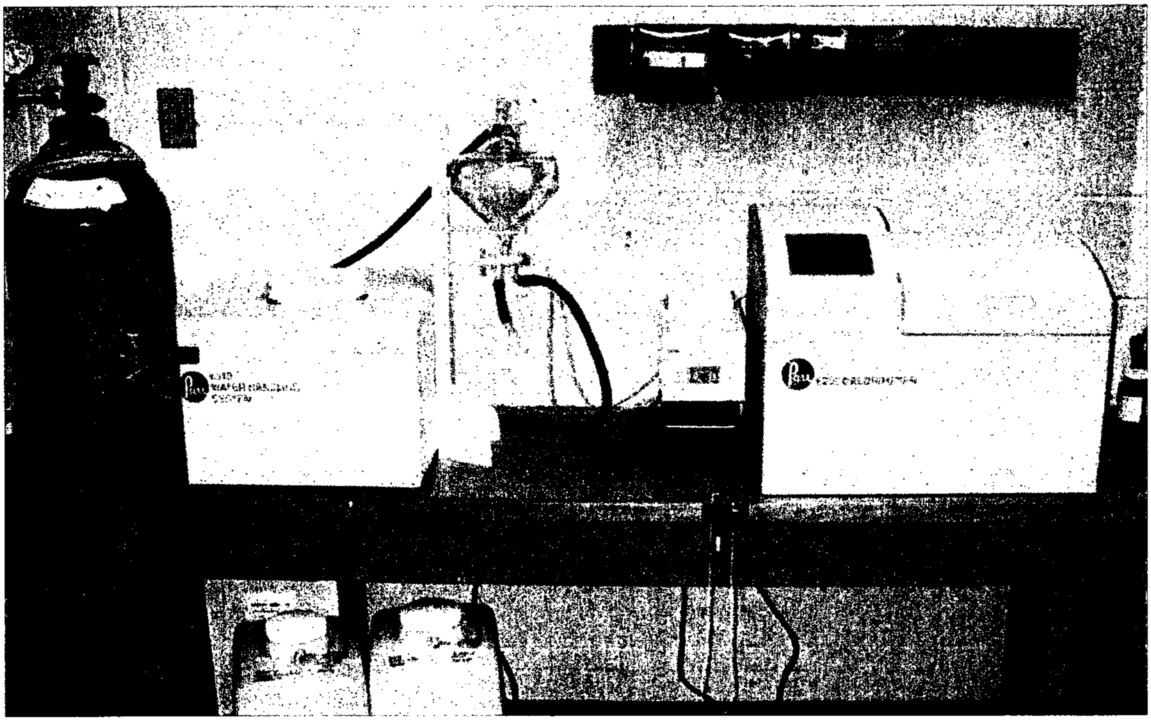


Figure 7. Parr 6200 Oxygen bomb Calorimeter (right) and Parr 6510 water handling system (left). Source: Hosegood 2008

All samples run through the bomb calorimeter are first weighed while in an oven dry state. This was ensured by placing opened specimen containers in the drying oven and by weighing until a constant mass was reached. The sample is pressed into 1±0.5 g pellets using a Parr Pellet Press. The pellet is then weighed on a Mettler AJ 100 scale to 0.1 mg accuracy in the crucible used in the bomb. The crucible and pellet are then set into the bomb where the fuse wire is installed and the bomb is sealed. The bomb is then filled to 450 psi with pure Oxygen to ensure a complete combustion of the pellet and quick release of the reaction energy. The bomb is placed into a bucket which is filled with 2000±0.5 ml of distilled water which is also 3-5 °C below the jacket temperature of 30°C. This is accomplished easily by the Parr 6510 water handling system which regulates the temperature of the distilled water and also has a 2000±0.5 ml automatic pipette to fill the bucket. The bomb is submerged in the bucket and placed within the calorimeter where it is connected via two fuse wires. The lid is closed and the operator begins the calorimeter run allowing the combustion of the sample to take place. The combustion of the sample releases the energy which is stored in the sample pellet and will increase the temperature of the water it is submerged in. The calorimeter detects the temperature change and waits until the final equilibrium condition of the water is met after which the temperature is recorded. This can take from 5 to 10 minutes after the combustion of the sample. Once the required conditions for the final equilibrium temperature are met the calorimeter takes a temperature reading and calculates the gross heat of combustion. The calorimeter calculates the gross heat of combustion using equation (3) and stores the results in its internal memory and also prints out a hard copy of the results.

$$H_c = \frac{(W \times T) - e_1 - e_2 - e_3}{m} \qquad [3]$$

Where,

H_c = Gross heat of combustion (MJ/kg).

T = Observed temperature rise (°C).

W = Energy equivalent of the calorimeter and bomb bucket combination being used (MJ/°C).

e_1 = Heat produced by the burning the nitrogen portion of the air trapped in the bomb to form nitric (MJ).

e_2 = Heat produced by the formation of sulphuric acid from the reaction of sulphur dioxide, water and oxygen (MJ).

e_3 = Heat produced by the fuse wire and cotton thread (MJ).

m = The mass of the sample (kg).

2.2.5 Statistical Analysis and Experimental Design

This experiment was designed to test the hypotheses, if there is an effect of site, tree species and tree component on calorific values. This study's selected sites, tree species and tree components were as factors in the analysis of variance (ANOVA) test. Prior to statistical analysis, homogeneity was tested and the data was found to be normally distributed. ANOVA was run to test if the three null hypotheses were rejected. If rejected, Duncan's test was run to explore if certain site, species and components could be grouped into similar subsets. Using the General Linear Model Method in SPSS Statistics 17, the hypotheses of this chapter were tested. The objectives expressed as a null hypotheses are:

H_1 = Site does not affect calorific values.

H_2 = Tree species does not affect calorific values.

H_3 = Tree component does not affect calorific values.

The linear model used to explain the experimental design is a full factorial design with the experimental units being each specific component sampled from a tree. With four repetitions of each of the six components of the seven species at each of the two sites the experimental size is 336. The linear model for this experiment is presented in equation 4:

$$Y_{ijkl} = \mu + A_i + S_j + C_k + AS_{ij} + AC_{ik} + SC_{jk} + ASC_{ijk} + \epsilon_{(ijk)l} \qquad [4]$$

$i = 1,2 \quad j = 1,2,3,4,5,6,7 \quad k = 1,2,3,4,5,6 \quad l = 1,2,3,4$

Where;
Y_{ijkl} = the average calorific value of the l^{th} replicate, k^{th} component, j^{th} species and i^{th} site.
μ = the grand mean.
A_i = the fixed effect of the i^{th} of two levels of site.
S_j = the fixed effect of the j^{th} of seven levels of tree species.
C_k = the fixed effect of the k^{th} of six levels of component.
AS_{ij} = the interaction effect of i^{th} site with j^{th} species.
AC_{ik} = the interaction effect of i^{th} site and k^{th} component.

SC_{jk} = the interaction effect of jth species and kth component.
ASC_{ijk} = the interaction effect of ith site, jth species kth component.
$\epsilon_{(ijk)l}$ = the random effect of lth rep within ith site, jth species and kth component.

2.3 RESULTS

The calorific value (CV) data collected from the calorimeter, which is presented in Appendix 1 and summarized in Table 3, were analysed using two statistical methods ANOVA and Duncan's test. The data set was found to have grand mean of 20.65 MJ/kg, with a standard deviation of 1.54 MJ/kg. The maximum value of 26.80 MJ/kg occurred in white birch lower bark at the Atikokan site. The minimum value was in the lower bark of black ash at the Atikokan site and was 18.07 MJ/kg. The ANOVA results are presented in Table 4. Table 4 shows that there was no significant difference between the sites. This allows the species and components to be analysed as if they were from one site. Significant differences were found for all other terms including 2-way and 3-way interactions with significant levels indicated in Table 4. The interaction effects between species and component are shown in Figure 8.

Table 3. Average calorific values of tree species and their components in MJ/kg.

Species	Tree Components					
Thunder Bay Site	Lower Bole	Lower Bark	Upper Bole	Upper Bark	Branch	Foliage
Ab	19.21	18.35	19.41	18.85	19.64	19.36
Bf	19.88	21.13	19.97	21.74	20.47	22.57
Bw	19.78	24.54	19.77	24.64	20.69	21.10
Pj	19.56	21.58	19.73	21.01	20.27	22.45
Po	19.68	22.25	19.59	21.57	21.03	21.68
Sb	19.18	20.58	19.26	20.24	21.41	21.35
Ta	19.98	21.10	19.97	21.41	20.15	21.47
Atikokan Site						
Ab	18.99	18.07	19.17	18.27	19.12	19.13
Bf	19.90	21.52	20.24	20.83	21.04	23.06
Bw	19.67	26.80	20.12	24.37	21.28	20.97
Pj	20.25	21.78	20.03	20.30	20.57	22.19
Po	19.44	22.63	19.90	22.52	21.20	21.40
Sb	19.56	19.88	19.51	19.59	20.55	20.74
Ta	19.44	20.94	19.71	20.73	20.12	21.13

Table 4. ANOVA results.

Source	Sum of Squares	df	Mean Square	F-value	Sig
Site	.043	1	0.043	0.150	ns
Species	250.430	6	41.738	145.604	***
Component	188.828	5	37.766	131.745	***
Site * Species	7.619	6	1.270	4.430	***
Site * Component	4.349	5	.870	3.035	*
Species * Component	250.352	30	8.345	29.112	***
Site * Species * Component	15.744	30	.525	1.831	**
Error	72.238	252	.287		

* = significant at α=0.05.
** = significant at α=0.01.
*** = significant at α=0.001.
ns = not significant

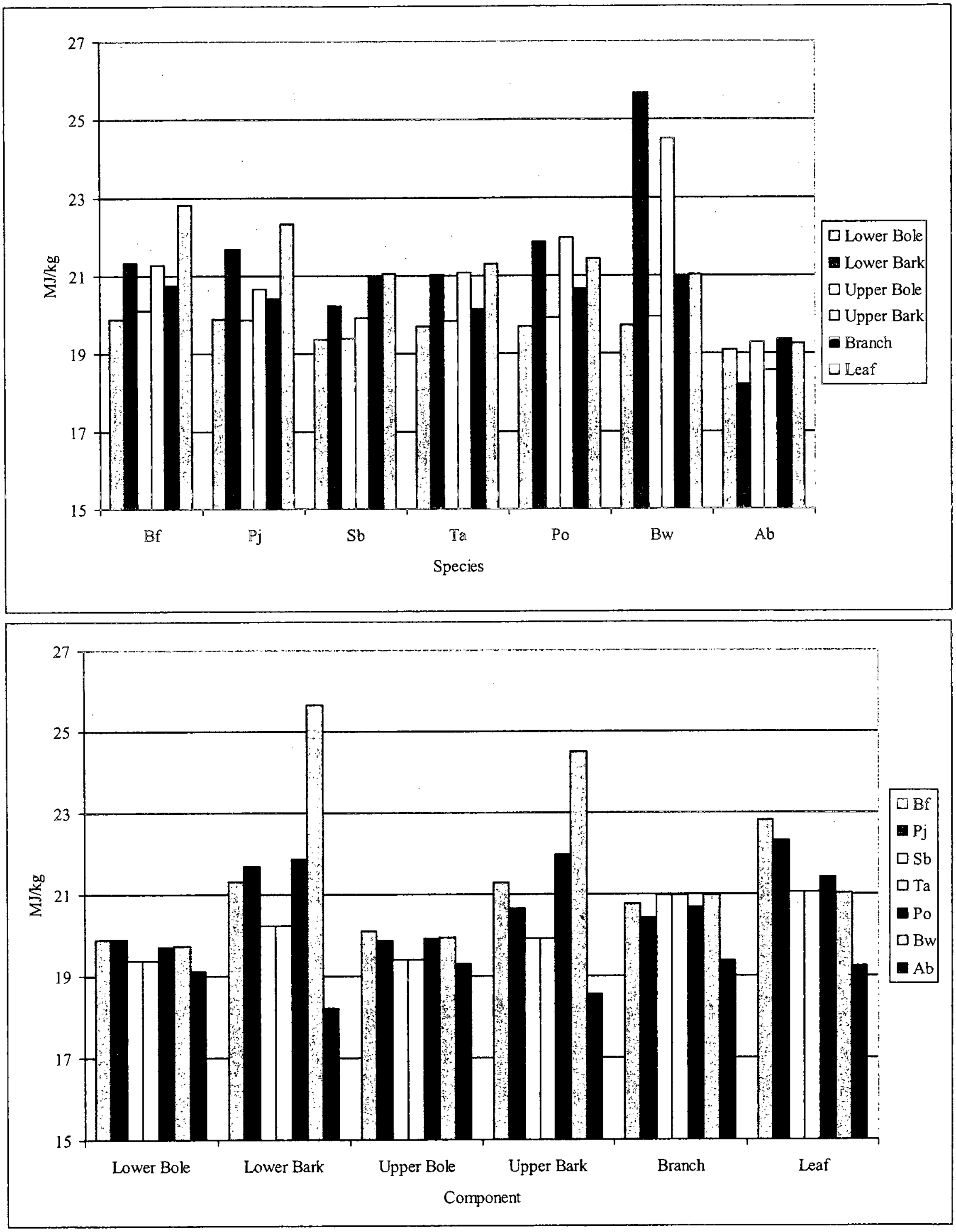
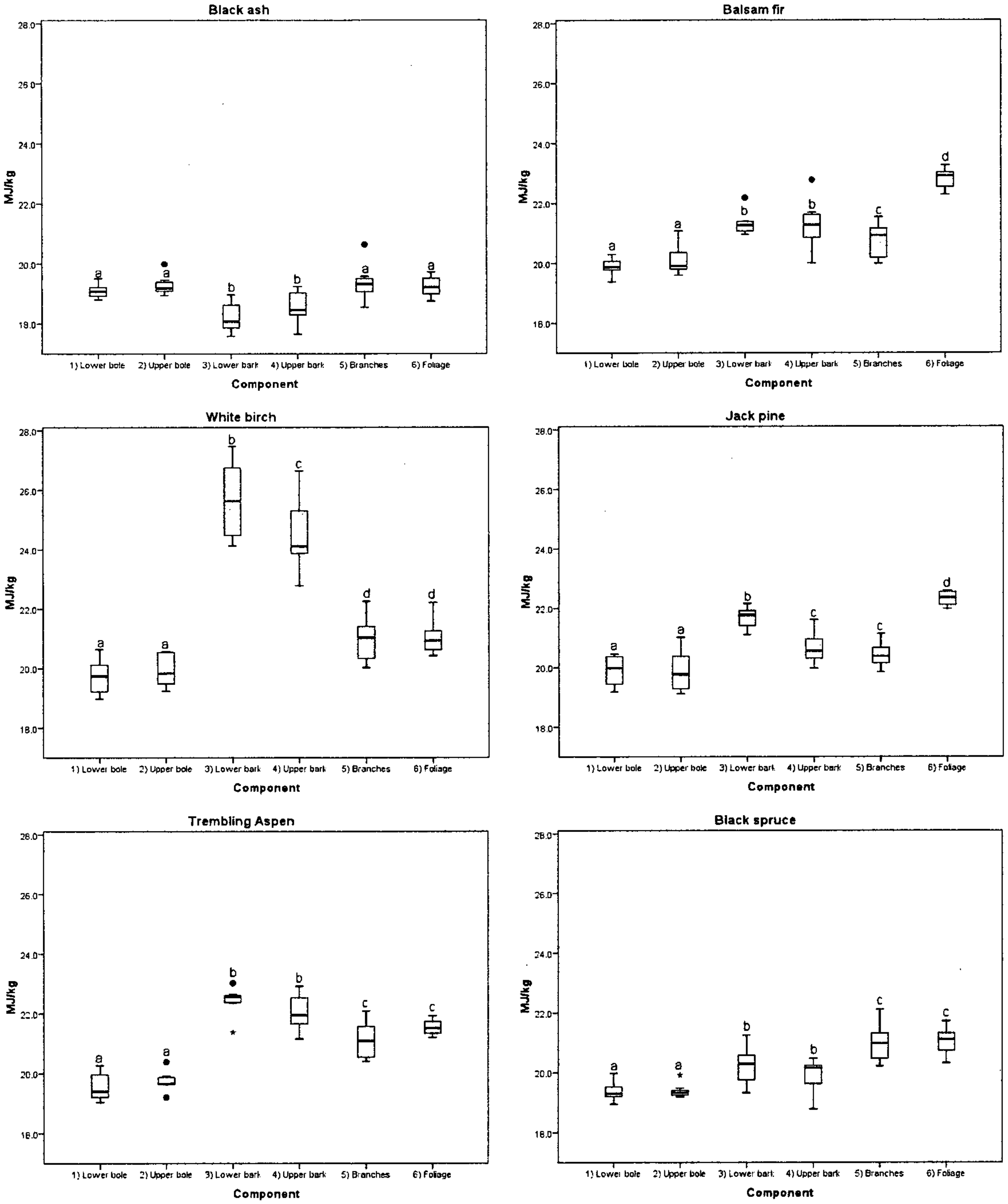


Figure 8. Interactions between the CV of species and components with both represented on the x-axis.

Box plots were used to further explore the species component interaction. These treatments were plotted on the x-axis (Figure 9, Figure 10). Duncan's test was used to provide groupings within treatment sets. Using Duncan's test certain trends through the different species (Figure 9) are now apparent. For every species lower bole and upper bole were grouped together. There were also tendencies to group lower bark and upper bark together which occurred in 5 of the 7 species. For the branches and foliage components, the grouping was species specific.

For components (Figure 10) there was only one trend between each of the components, with the exception of wood components, black ash is not able to be grouped with any other species. Within similar components similarities do appear. In lower bole, all species other than black ash belong to one group. Upper bole components have a similar trend where all but black ash belongs to two overlapping groups. Both bark components have the same groupings; balsam fir, jack pine, and tamarack make up one group with all other species in four unique groups. The branches component had three groups with all species but black ash within two overlapping groups. Foliage is the most species specific component, six groups were created by Duncan's test with only balsam fir in multiple groups.



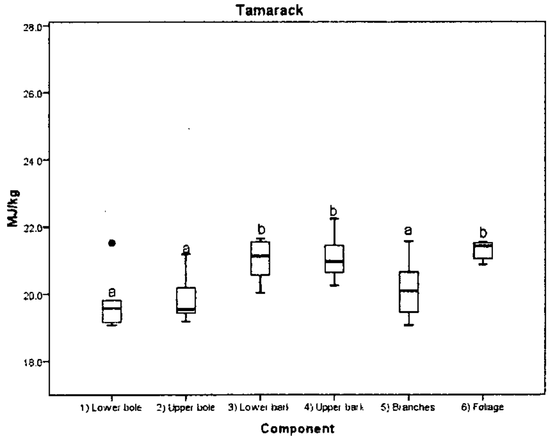


Figure 9. The two way interaction of CV of species and components with different graphs for each component. Letters above each boxplot indicate groups of species within a component from Duncan's test. Similar letters indicate no significant difference.

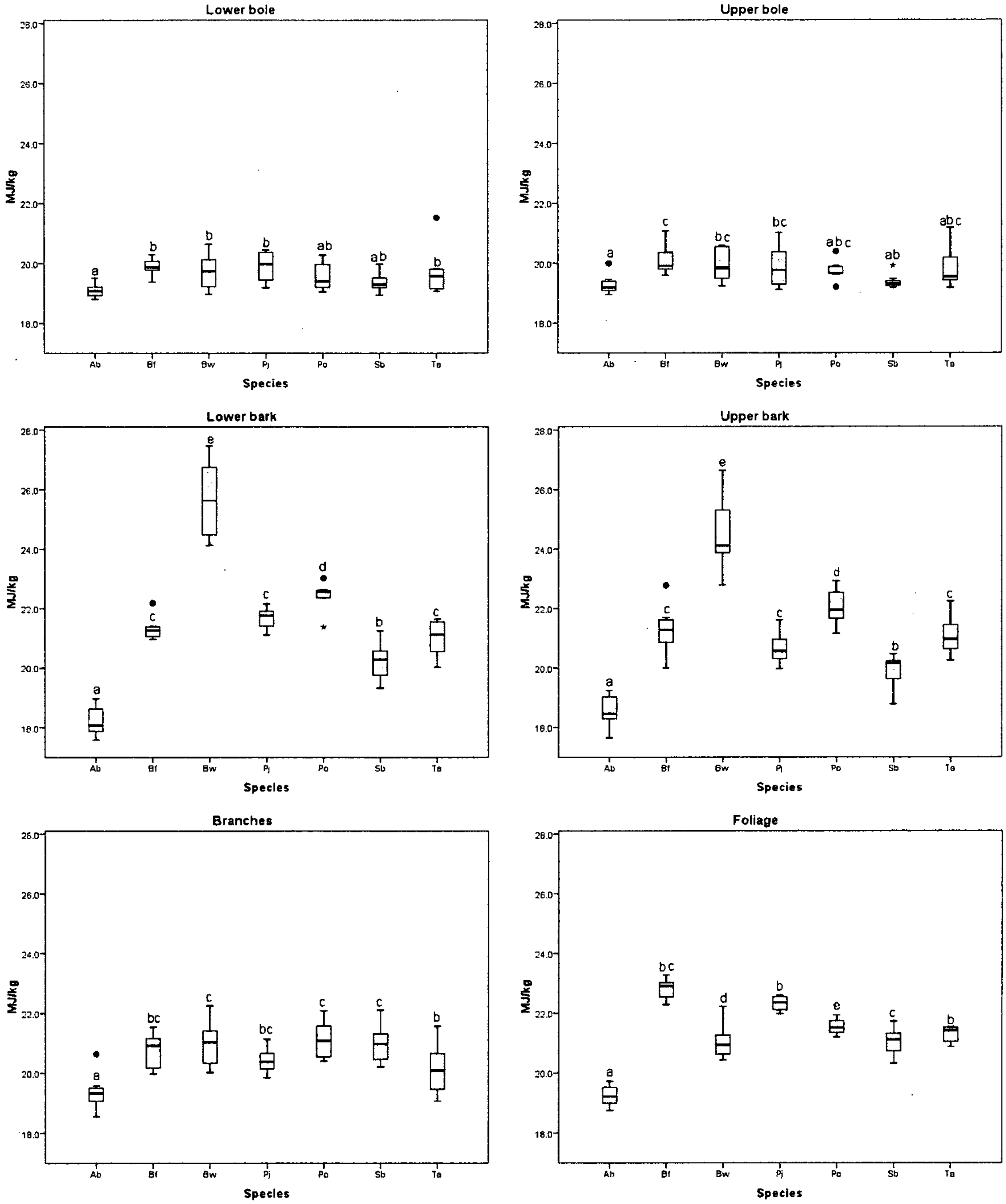


Figure 10. The two way interaction of CV of component and species. Letters above each boxplot indicate groups of species within a component from Duncan's test. Similar letters indicate no significant difference.

2.5 DISCUSSION

A significant difference was found between the species and between the components sampled but no statistical difference was found between the sites sampled. Species were found to be much more unique than expected and were shown to be different within the group with the exception of trembling aspen and balsam fir. It was surprising the three hardwood and four softwood trees species did not display any similarities due to physiological similarities within each group. Even the wood in the two groups were not as different as described in section 1.2.2.2 Tree Species. Average calorific values of both lower and upper bole wood for softwoods were found to be 19.76 MJ/kg and hardwoods 19.62 MJ/kg. A relatively minor difference considering the difference in cellulose, hemicellulose and lignin (Panshin and DeZeeuw 1980, Jane 1956) and their different caloric content (Chandler 1983, Howard 1973, White and Plaskett 1981, Baker 1983, Tillman 1978).

Although interaction terms with the site were found to be significant it is important to note that the overall means were nearly equal and therefore the geographical difference described in Nurmi (1993) may only apply to latitude and not longitude. Nurmi (1993) sampled trees from Midwestern Finland where growth rates are comparable with the northwestern Ontario area, while the other sample site was located approximately 500 km north near the tree line where tree growth rate is minimal. Results by this study show that longitude does not necessarily play an important role in determining calorific content of trees. By comparing these two studies it seems that it may take greater distances between sites then used in this study for significant differences to occur. It may also be that trees from different longitude do not have significant differences in calorific values, whereas trees with different latitudes do have.

Perhaps growth rate should be investigated to explain geographic variation of calorific values in trees. Although growth rate may not be the sole factor in the variation of calorific values in trees as it has been found that there is no correlation between wood density and calorific values (Doat 1977) and earlywood and latewood was not found to be a significant factor in calorific values of wood (Howard 1973). These are two factors which vary at differing growth rates but are not the only two factors affected.

The work completed by Singh and Kostecky (1986) report calorific means for each component which range from 19.12 to 21.10 MJ/kg for softwoods and 18.40 to 20.09 for hardwoods. In this study it was found that calorific value of components means ranged from 19.18 to 23.06 MJ/kg for softwoods and 18.07 to 26.80 MJ/kg for hardwoods. Kryla (1984) found that tree species native to Canada had a mean calorific value of 21.18 MJ/kg for softwoods and a value of 19.35 MJ/kg for hardwoods. This fell within the ranges of calorific values found by this study for softwoods and hardwoods. When compared to previous studies we can see that there are clear differences in both calorific value range for species and components as well as general calorific value averages for hardwoods and softwoods. The previously published range for calorific values is much smaller than shown by this study. Having larger ranges for calorific values further increases the importance of both knowing the calorific value of each species and their components as well as knowing what harvesting residue is being utilized. General calorific value averages for hardwoods and softwoods are another clear difference found when comparing this study to previous work (Kryla 1984). This study found just small amounts of variation between hardwoods and softwoods. If only previously published data were considered while planning biomass acquisition, hardwood species may have been avoided due to their inferior published heating potential. Now hardwoods trees in northern Ontario could be used for this purpose due to their equal heating values, their abundance and current low value commercial use.

There are also differences in previously published data and specific tree components investigated by this study. All components can be compared from Table 1 (previously published data) and Table 3 (this study's results) with only the interesting and major differences discussed here. The softwoods studied seemed to correspond well with the highest values found in the published literature (Table 1). However, if the lowest published values were used to describe calorific value in northwestern Ontario an underestimate would be made. Examples of this are apparent when considering the lower bole component of balsam fir and the lower bark component of jack pine which are underestimated by as much as1.14 MJ/kg and 1.47 MJ/kg, respectively. Hardwood trees seem to produce the most interesting and important values of this study. Calorific values of black ash were crucial due to the complete lack of literature published on this species. Black ash produced calorific values which were different from almost every other species and component. Trembling aspen also produced results that were unexpected as it is generally held as having poor heating values. This study showed it was higher than most published data (Table 1) and displayed calorific values as high as most other species (Kryla 1984, Singh and Kostecky 1986). White birch, which was regarded as having high calorific values still produced higher than expected results. White birch bark and wood displayed calorific values higher than previously published data (Table 1, Table 3).

Knowing the calorific content of the tree species and their components in northwestern Ontario gives the local bioenergy sector advantages over potential competitors. Having recently completed accurate data surrounding potential biomass sources allows area businesses trying to secure investment funding an advantage over other areas. This data can be used to strengthen business proposals by providing concrete data on the specifics of the biomass available for energy.

CHAPTER 3

SPECIFIC GRAVITY

3.1 INTRODUCTION

Specific gravity is a characteristic which adds to the calorific value knowledge gained in Chapter 2. Knowing the specific gravity and calorific value of available biomass allows the calorific value per unit volume to be known. Calorific value per unit volume is crucial when beginning to move biomass from one location to another. This information can be used to determine cost effective haul distance, energy per truck load and aid in determining the feed rate into a boiler. Specific gravity can be extremely variable between different sites, tree species and tree components (Panshin and DeZeeuw 1980, Wiemann and Williamson 2002) and has a large impact in determining the calorific value of an object because it is an indication of the total mass. The published data on specific gravity of wood in the northwestern Ontario tree species studied ranges from 0.35 to 0.55 (Table 2).

The objectives of this chapter are to examine the specific gravity of common northwestern Ontario trees and their components. More specifically, to test if there are differences in specific gravity between the two study areas; if there are differences between species; and if there are differences between components of a tree. Similar tree species and components will be grouped into subsets to reveal any similarities within a treatment group. This information will also be used to augment the database on northwestern Ontario's tree species calorific values to further understand the fuel characteristics in the area.

3.2 METHODOLOGY

3.2.1 Study Area

The study area is the same as described in section 2.2.1.

3.2.2 Field Sampling

Field sampling techniques were the same as described in section 2.2.2.

3.2.3 Sample Preparation

Samples were cut from original sample material described in section 2.2.2. To increase accuracy as well as laboratory efficiency samples were cut in standard irregular patterns which were all well over the minimum recommended size of 1 cm^3 although samples were generally much larger then that to increase accuracy. Wood was cut using a 19" General band saw in a pie shape from pith to bark to represent juvenile and mature wood in the same proportions as is present in the tree. It was also ensured that the wood sampled contained no less than five growth rings. Bark and branches were prepared to the standards for wood as there are no separate standards available for these materials. Bark was cut using pruning shears in an approximate square pattern. Branches were cut using a band saw in a cylindrical section containing both bark and wood. All samples were then labelled and placed inside a drying oven and weighed until a constant mass was reached.

3.2.4 Determination of Specific Gravity

Following ASTM standard D2395-07a and ISO standard 3131-1975(E), the following procedures were used to determine the specific gravity of all samples with the exception of foliage. Due to limitations in the laboratory, specific gravities of foliar samples were not determined. The specific gravity of all samples was tested in duplicate and averaged using the following procedures.

To obtain specific gravity, the oven dry weight of the sample was taken using a Mettler AJ 100 scale to 0.1 mg accuracy. Once this weight is recorded, the volume of the sample must be determined. Due to irregular shapes of samples, the volume was obtained by using the water immersion technique. The amount of displaced water can be measured in two ways, by measuring the volume of water displaced or by measuring the mass of the water displaced. To increase the accuracy of the volume measurement, the mass of the water displaced was used. This technique involves placing a beaker which is large enough to submerge the sample on a scale filled with distilled water and the scale tared. The sample is attached to a metal pin and submerged into the water where the weight of displaced water is recorded as grams. The weight in grams can be converted directly into cm^3 as the two are numerically equal for distilled water at 4°C.

Once both the oven dry (OD) weight and the OD volume, obtained from the weight of displaced water, of the samples are known the specific gravity can then be calculated using equation 5:

$$SG = \frac{OD \quad weight}{Weight \quad of \quad displaced \quad volume \quad of \quad water} \qquad [5]$$

3.2.5 Statistical Analysis and Experimental design

This study's selected sites, tree species and tree components were all outlined in the previous section and will be used as factors in the analysis of variance (ANOVA) test. Using the General Linear Model Method in SPSS Statistics 17, the objectives of this chapter will be tested. The objectives expressed as a null hypotheses are:

H_1 = Site does not affect specific gravity of tree components.

H_2 = Tree species does not affect specific gravity of tree components.

H_3 = Tree components does not affect specific gravity of tree components.

The linear model used to explain the experimental design is a full factorial design with the experimental units being each specific component sampled from a tree. With four repetitions of each of the five components of the seven species at each of the two sites the experimental size is 280. The linear model for this experiment is represented in equation 6:

$$Y_{ijkl} = \mu + A_i + S_j + C_k + AS_{ij} + AC_{ik} + SC_{jk} + ASC_{ijk} + \epsilon_{(ijk)l} \qquad [6]$$

$i= 1,2 \quad j= 1,2,3,4,5,6,7 \quad k= 1,2,3,4,5 \quad l= 1,2,3,4$

Where,
Y_{ijkl} = the specific gravity of the l^{th} replicate, k^{th} component, j^{th} species and i^{th} site.
μ = the grand mean.
A_i = the fixed effect of the i^{th} of two levels of site.
S_j = the fixed effect of the j^{th} of seven levels of tree species.
C_k = the fixed effect of the k^{th} of six levels of component.
AS_{ij} = the interaction effect of i^{th} site with j^{th} species.
AC_{ik} = the interaction effect of i^{th} site and k^{th} component.
SC_{jk} = the interaction effect of j^{th} species and k^{th} component.
ASC_{ijk} = the interaction effect of i^{th} site, j^{th} species k^{th} component.
$\epsilon_{(ijk)l}$ = the random effect of l^{th} rep within i^{th} site, j^{th} species and k^{th} component.

3.3 RESULTS

The data collected for specific gravity is presented in Appendix 2 and summarized in Table 5. The data was analysed using two statistical methods ANOVA and Duncan's test if significant differences existed. ANOVA was run to test if the three null hypotheses will be rejected. If any of the hypotheses were rejected, Duncan's test was run to explore if certain species and components could be grouped into similar subsets. The data set was found to have grand mean of 0.607, with a standard deviation of 0.108. The maximum value which occurred in trembling aspen upper bark was 0.882 and the minimum value was in the lower bole of balsam fir and was 0.373. The ANOVA results are presented in Table 6. Table 6 shows that significant differences were found for the three treatments. Significant differences were found for the species and site as well as species and component interaction terms. The other two terms, the last 2-way and the only 3-way interactions, were not significant. The level of significance is indicated in Table 6. The interaction effects between species and component are shown in Figure 11.

Table 5. Specific gravity of tree species and components at both sites.

Thunder Bay	Specific Gravity Averages				
Species	Lower Bole	Lower Bark	Upper Bole	Upper Bark	Branches
Ab	0.617	0.565	0.615	0.625	0.688
Bf	0.373	0.697	0.396	0.695	0.563
Bw	0.576	0.610	0.600	0.594	0.654
Pj	0.476	0.622	0.464	0.720	0.536
Po	0.427	0.742	0.460	0.821	0.528
Sb	0.516	0.730	0.578	0.696	0.664
Ta	0.596	0.664	0.574	0.619	0.584
Atikokan					
Ab	0.651	0.568	0.645	0.671	0.702
Bf	0.396	0.705	0.442	0.710	0.633
Bw	0.675	0.676	0.652	0.613	0.652
Pj	0.471	0.640	0.468	0.721	0.568
Po	0.513	0.689	0.501	0.882	0.563
Sb	0.495	0.685	0.488	0.739	0.683
Ta	0.617	0.675	0.547	0.676	0.563

Table 6. ANOVA results.

Source	Sum of Squares	df	Mean Square	F	Sig.
Site	0.027	1	0.027	13.582	***
Species	0.215	6	0.036	17.801	***
Component	1.312	4	0.328	163.057	***
Site * Species	0.029	6	0.005	2.365	*
Site * Component	0.013	4	0.003	1.563	ns
Species * Component	1.151	24	0.048	23.848	***
Site * Species * Component	0.063	24	0.003	1.295	ns
Error	0.422	210	0.002		

* = significant at $\alpha=0.05$.
** = significant at $\alpha=0.01$.
*** = significant at $\alpha=0.001$.
ns = not significant

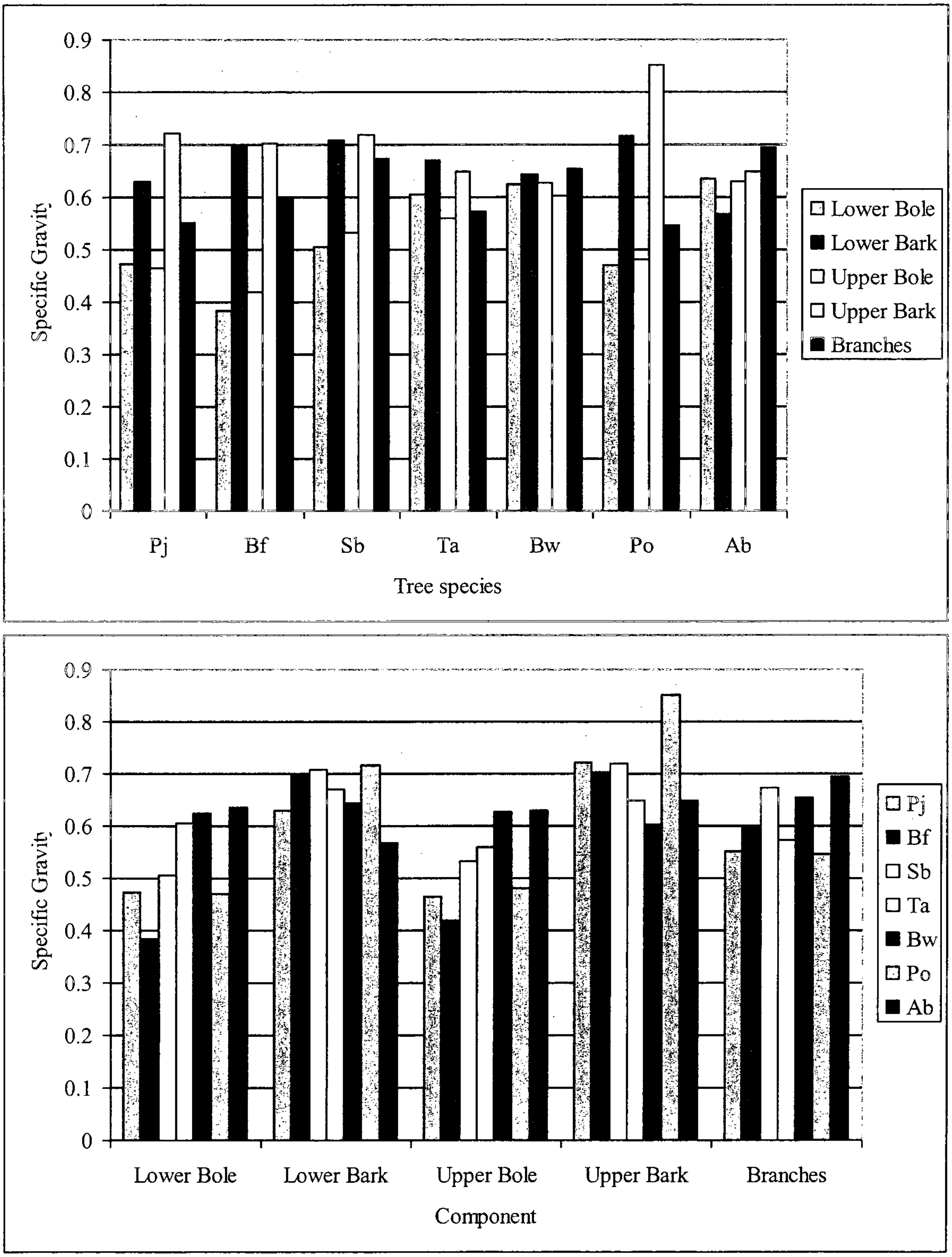


Figure 11. Interactions between the specific gravity values of species and component treatments with both represented on the x-axis.

Box plots were used to further explore the site-species interaction (Figure 12) and the species-component interaction these treatments were plotted with each on the x-axis (Figure 13, Figure 14). Duncan's test was used to provide groupings within treatment sets. The two sites produced similar overlapping groupings between the species groups (Figure 12). This is due to each of the species group having a high amount of variability due to it containing all six of the different components. Using Duncan's test certain trends through the different species (Figure 13) are now apparent. For every species lower bole and upper bole were grouped together. Beyond the grouping for the wood components the groupings were very species specific which ranged from having all components in one group to every component other then wood in its own group. For components the groups created were very component specific and no real trends exist between the different components (Figure 14). The groupings are different between every component and no species are grouped together throughout the components.

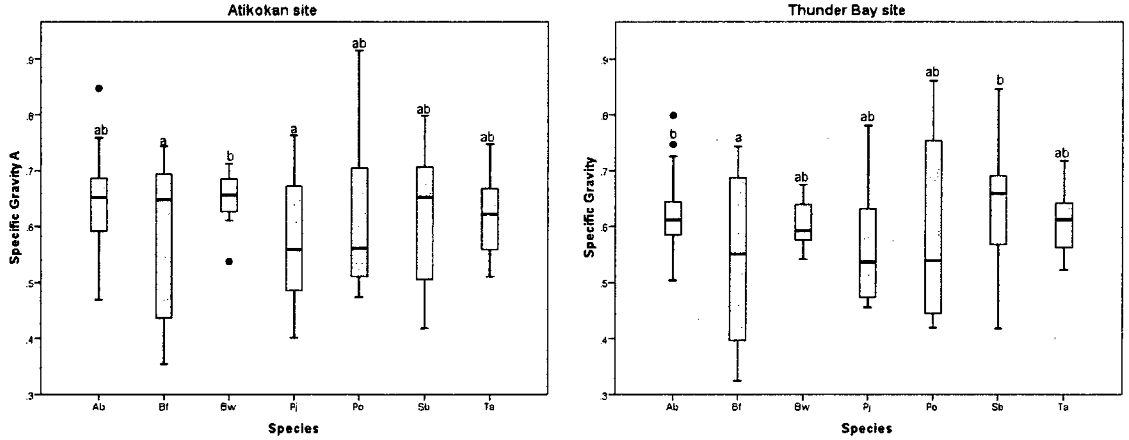


Figure 12. The two way interaction of specific gravity values of site and species with different graphs for each site. Letters above each boxplot indicate groups of species within a site from Duncan's test. Similar letters indicate no significant difference.

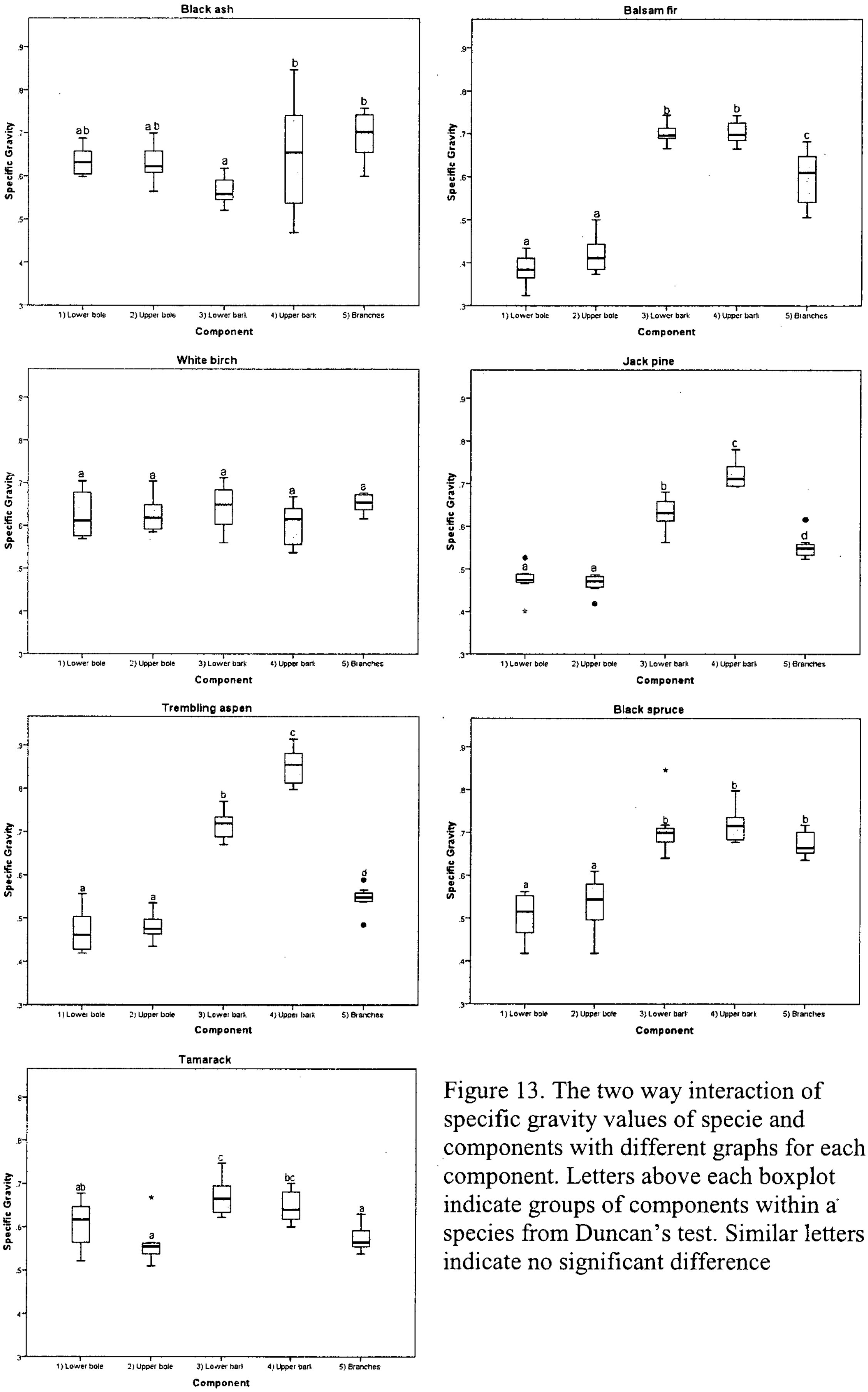


Figure 13. The two way interaction of specific gravity values of specie and components with different graphs for each component. Letters above each boxplot indicate groups of components within a species from Duncan's test. Similar letters indicate no significant difference

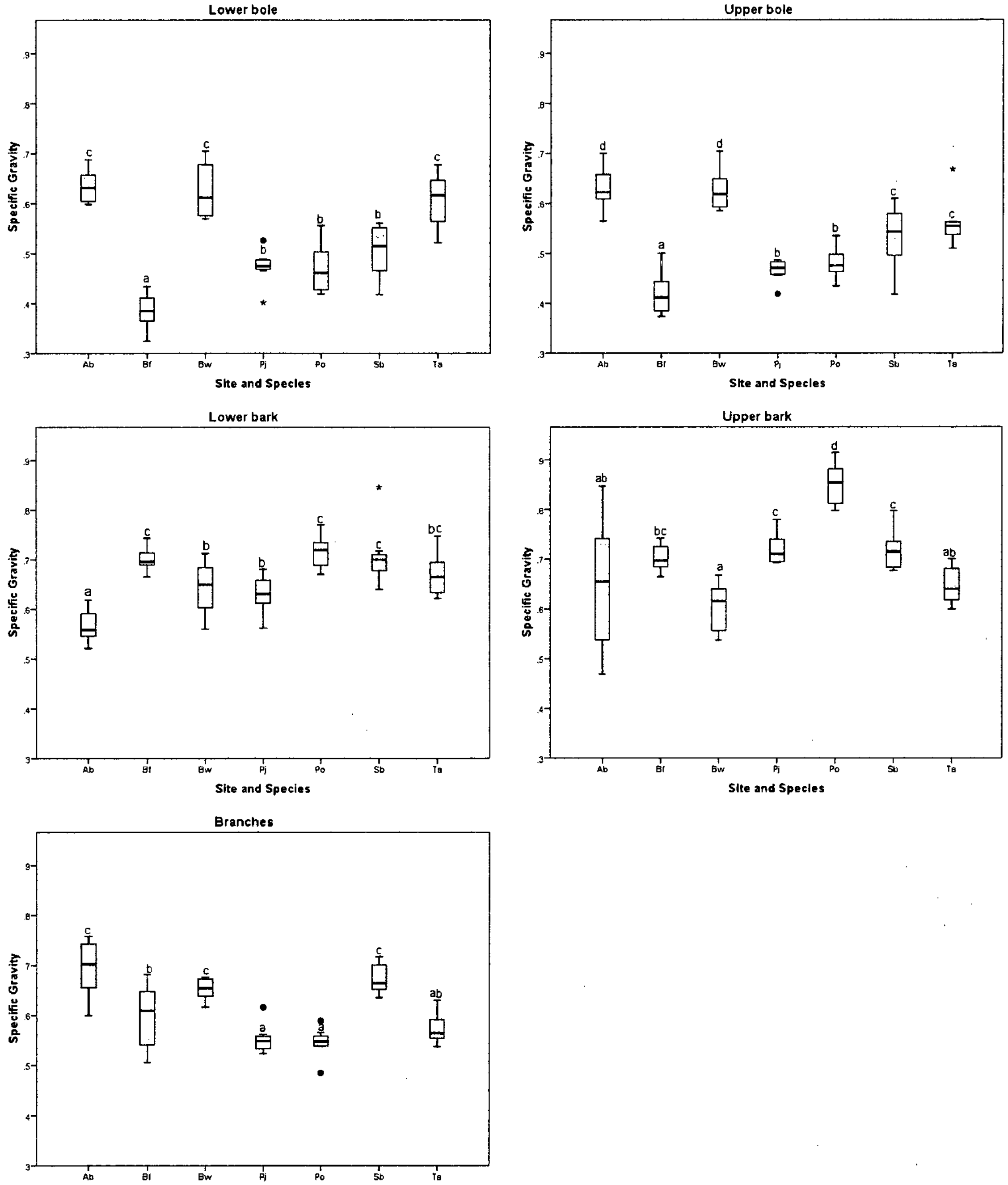


Figure 14. The two way interaction of specific gravity values of component and species with a different graph for each component. Letters above each boxplot indicate groups of species within a component from Duncan's test. Similar letters indicate no significant difference

3.4. DISCUSSION

The objectives of this chapter, to investigate the specific gravity of different tree species and their components at different sites, were completed. This knowledge can now be applied to the management of biomass as specific gravity will drastically affect haul cost and efficiency. This database can be used in northwestern Ontario by forest managers to seek out species and component which have a high energy per unit volume.

A significant difference was found between the sites, species and components sampled. The two sites sampled were found to be significantly different which comes as no surprise as specific gravity is influenced by growth rate and therefore site characteristics (Panshin and DeZeeuw 1980, Wiemann and Williamson 2002). These two sites were found to be significantly different and this should be considered when planning biomass acquisition. Tree species was also found to be significantly different, which was also expected because of different growth patterns and cell types contained within the trees (Panshin and DeZeeuw 1980, Wilson 1984 Hoadley 1990). The largest difference in tree species is due to the two major tree types, hardwood and softwood, which were shown to have different specific gravities (Simpson 1999). Tree component was also found to be statistically different and due to lack of previously published data in this area there were no expectations. Both bark components were found to have the highest specific gravity of all the components with upper bark being the highest. Bark does tend to be denser than wood due to higher lignin concentration as well as collapsed cells which remove some air space and increase the specific gravity (Panshin and DeZeeuw 1980).

When the interaction between species and component is considered, the variation between each component and species is revealed. Figures 13 shows that the relationship of species and components seem to be extremely species specific making no apparent pattern. If the instances of trembling aspen and black ash are considered it is seen that the specific gravity of poplar bark is much higher than the wood but black ash's bark is not significantly different than its wood. A unique relationship between component and species are also present (Figure 14). No grouping of species remain constant throughout each of the components.

Although there is limited literature on the components of the trees which were not wood comparisons between the wood components will be made. The wood components were combined and the averages reported in Table 7. It is made very apparent in Table 7 that the wood in the sample sites is considerably higher for every species than previous published data. The most interesting differences are found in black spruce and trembling aspen which are 0.1 higher and black ash which was 0.13 higher.

Table 7. Previously published specific gravities compared with both wood component results.

Tree Species	Specific Gravity of wood		
Black spruce	0.42[a]	0.42[b]	0.52[c]
Balsam fir	0.35[a]	0.36[b]	0.40[c]
Jack pine	0.40[a]	0.38[b]	0.47[c]
Tamarack	0.53[a]	0.53[b]	0.58[c]
White birch	0.55[a]	0.55[b]	0.63[c]
Trembling aspen	0.38[a]	0.38[b]	0.48[c]
Black ash	0.49[a]	0.49[b]	0.63[c]

[a] indicates source of information is USDA 1987

[b] indicates source of information is Hoadley 1990

[c] indicates source of information is Appendix 2

The specific gravity in the area has two valid explanations, which both factor into the high values found in this study. First textbooks (USDA 1987 and Hoadley 1990) as well as most other sources for specific gravity use averages of many studies. This average is more representative of a species as a whole but does not represent local specific gravities as well as they could. The second explanation for the high specific gravity found in wood is that major factors in specific gravity in the wood are the cell wall thickness and cell size (Panshin and DeZeeuw 1980). The average cell wall thickness increases throughout wood as growth rate decreases due to increasing percentage of latewood (Panshin and DeZeeuw 1980). Latewood has thicker cell walls than earlywood and decreases the amount of airspace in wood while increasing cell wall material.

CHAPTER 4

ASH CONTENT

4.1 INTRODUCTION

Ash content can be a crucial fuel characteristic to allow a biomass source to be profitably used in the production of green energy. Knowing the ash content of potential sources of biomass can allow proper mixing and sorting to ensure ash content is within boiler thresholds (FERIC 2008). Ash content can be extremely variable in different sites, tree species and tree components (Hakkila 1989, Demeyer et al. 2001) and can drastically reduce the fuel quality by decreasing the calorific value and increasing the cost for ash removal and disposal.

While the other two fuel characteristic explored measured pre-combustion characteristics, ash content is the remaining non-combustibles. Ash content also has detrimental effects to the boiler itself and can cause fouling and slagging which can damage and reduce its efficiency (FERIC 2008, Monti et al. 2008).

The objectives of this chapter are to examine the ash content of forest harvesting residues and understand some of the factors which affect it. More specifically to test if a difference in ash content exists between the study areas; if there are differences between species; and if there are differences between components of a tree. Similar tree species and components will be grouped into subsets to reveal any similarities within a treatment group. This information will also be used to augment the database on northwestern Ontario's tree species calorific.

4.2 METHODOLOGY

4.2.1 Study Area

The study area is the same as described in section 2.2.1.

4.2.2 Field Sampling

Field sampling techniques were the same as described in section 2.2.2.

4.2.3 Sample Preparation

Sample preparations were the same as outlined in section 2.2.3.

4.2.4 Determination of Ash Content

The ash contents in all sample material were determined by following the laboratory procedures given by Sluiter et al. (2005) and ASTM Standard E1755-01. An appropriate amount of crucibles were marked with identifiers and placed in a muffle furnace at 575 +25°C for four hours. From this point crucibles were only handled using tongs to avoid adding weight from skin moisture or oils. This removed any moisture in the porcelain and will prevent weight loss from the container. The crucibles were removed from the muffle furnace and placed directly into a desiccator until used. All crucibles were then weighed at this bone dry state and the weight recorded for each individual crucible. The samples which were run must be at an oven dry state and to ensure these samples were weighed in tared crucibles to approximately one gram and then placed in a drying oven at 105°C for two hours. The samples and crucibles were reweighed and checked to be completely free of moisture. The samples were then ashed using a muffle furnace with a ramping program. The following was programmed into the muffle furnace to ensure proper ashing of samples:

Ramp from room temperature to 105 °C
Hold at 105°C for 12 minutes
Ramp to 250 °C at 10°C / minute
Hold at 250 °C for 30 minutes
Ramp to 575 °C at 20 °C / minute
Hold at 575 °C for 180 minutes
Allow temperature to drop to 105 °C
Hold at 105 °C until samples are removed

The crucibles were then placed in the muffle furnace and the ramping program was begun. While the samples were being handled to be put in or out of the muffle furnace they were protected from drafts to avoid any loss of sample. Once the program had run the crucibles were removed from the muffle furnace and put directly into a desiccator to cool. Once cooled each crucible and remaining ash was weighed to the nearest 0.1 mg and the weight was recorded. This procedure was repeated until all samples were run through the muffle furnace and ash content known. To calculate the ash content percentage equation 7 was used:

$$\% ASH = \frac{W_1 - W_2}{W_3 - W_2} \times 100 \qquad [7]$$

Where,

W_1= Weight of the crucible and ash (g).
W_2= Weight of the crucible (g).
W_3= Weight of the crucible and oven dry sample (g).

4.2.5 Statistical Analysis and Experimental design

This experiment was designed to test the objectives, if there is an effect of site, tree species and tree component on ash content. This study' selected sites, tree species and tree components were all outlined in the previous section and will be used as factors in the analysis of variance (ANOVA) test. Using the General Linear Model Method in SPSS Statistics 17, the objectives of this chapter will be tested. The objectives expressed as a null hypotheses are:

H_1 = Site does not affect ash content of tree components.

H_2 = Tree species does not affect ash content of tree components.

H_3 = Tree components does not affect ash content of tree components.

The linear model used to explain the experimental design is a full factorial design with the experimental units being each specific component sampled from a tree. With four repetitions of each of the six components of the seven species at each of the two sites the experimental size is 336. The linear model for this experiment follows equation 8:

$$Y_{ijkl} = \mu + A_i + S_j + C_k + AS_{ij} + AC_{ik} + SC_{jk} + ASC_{ijk} + \epsilon_{(ijk)l} \qquad [8]$$

$i = 1,2 \quad j = 1,2,3,4,5,6,7 \quad k = 1,2,3,4,5,6 \quad l = 1,2,3,4$

Where,

Y_{ijkl} = the ash content of the l^{th} replicate, k^{th} component, j^{th} species and i^{th} site.
μ = the grand mean.
A_i = the fixed effect of the i^{th} of two levels of site.
S_j = the fixed effect of the j^{th} of seven levels of tree species.
C_k = the fixed effect of the k^{th} of six levels of component.
AS_{ij} = the interaction effect of i^{th} site with j^{th} species.
AC_{ik} = the interaction effect of i^{th} site and k^{th} component.
SC_{jk} = the interaction effect of j^{th} species and k^{th} component.
ASC_{ijk} = the interaction effect of i^{th} site, j^{th} species k^{th} component.
$\epsilon_{(ijk)l}$ = the random effect of l^{th} rep within i^{th} site, j^{th} species and k^{th} component.

4.3 RESULTS

The data collected from ash content testing, which is presented in Appendix 3 and summarized in Table 8, was analysed using three statistical methods ANOVA and Duncan's test. ANOVA was run to test if the three null hypotheses will be rejected. Following the ANOVA Duncan's test was run to explore if certain species and components could be grouped into similar subsets. The data set was found to have a mean ash content of 2.33%, with a standard deviation of 2.21%. The maximum value which occurred in black ash lower bark was 9.19% and the minimum value was in the lower bole of jack pine and was 0.13%. For a species as a whole the highest average ash content was found to be in black ash with 4.98% and the lowest was in jack pine with 1.10%. The ANOVA results are presented in Table 9. Table 9 shows that significant differences were found for the three treatments. A significant difference was found for the species and component and the 3-way interaction term. The other 2-way interactions were not significant. The level of significance is indicated in Table 9. The interaction effects between species, component and site are shown in Figure 15 and Figure 16.

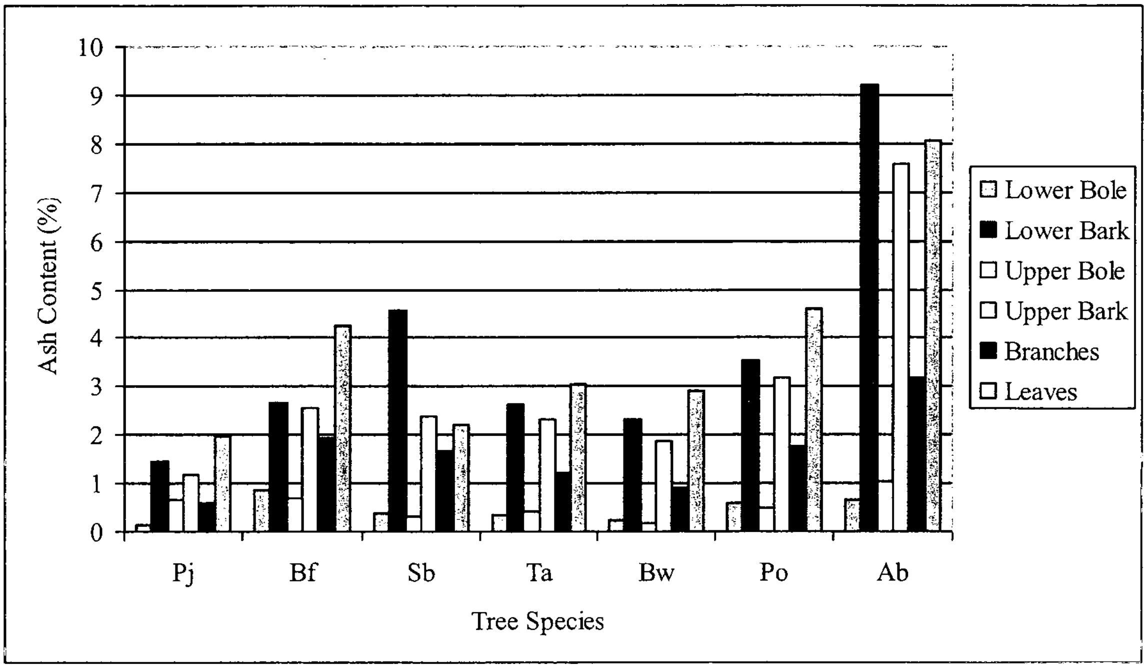
Table 8. Ash content of tree species and their components at each site in percent.

Species	Tree Components					
Thunder Bay	Lower Bole	Lower Bark	Upper Bole	Upper Bark	Branch	Leaf
Ab	0.648	9.188	1.049	7.583	3.181	8.072
Bf	0.850	2.665	0.675	2.561	1.927	4.272
Bw	0.229	2.317	0.189	1.867	0.886	2.897
Pj	0.133	1.452	0.669	1.171	0.588	1.965
Po	0.603	3.535	0.483	3.186	1.777	4.603
Sb	0.392	4.584	0.317	2.389	1.662	2.223
Ta	0.346	2.644	0.426	2.316	1.209	3.049
Atikokan						
Ab	0.645	8.212	1.186	7.631	3.531	8.799
Bf	0.814	2.988	1.129	4.648	1.891	3.798
Bw	0.307	1.962	0.418	2.851	1.643	6.185
Pj	0.202	1.640	0.660	1.798	0.738	2.239
Po	0.384	3.592	0.464	2.699	2.466	4.048
Sb	0.579	3.674	0.331	2.773	1.365	3.134
Ta	0.169	3.583	0.851	2.936	1.504	2.754

Table 9. ANOVA results.

Source	Sum of Squares	df	Mean Square	F	Sig.
Component	725.426	5	145.085	247.645	***
Species	440.855	6	73.476	125.416	***
Site	5.189	1	5.189	8.857	**
Component * Species	271.387	30	9.046	15.441	***
Component * Site	5.918	5	1.184	2.020	ns
Species * Site	6.668	6	1.111	1.897	ns
Component * Species * Site	30.688	30	1.023	1.746	*
Error	147.637	252	.586		

* = significant at α=0.05.
** = significant at α=0.01.
*** = significant at α=0.001.
ns = not significant



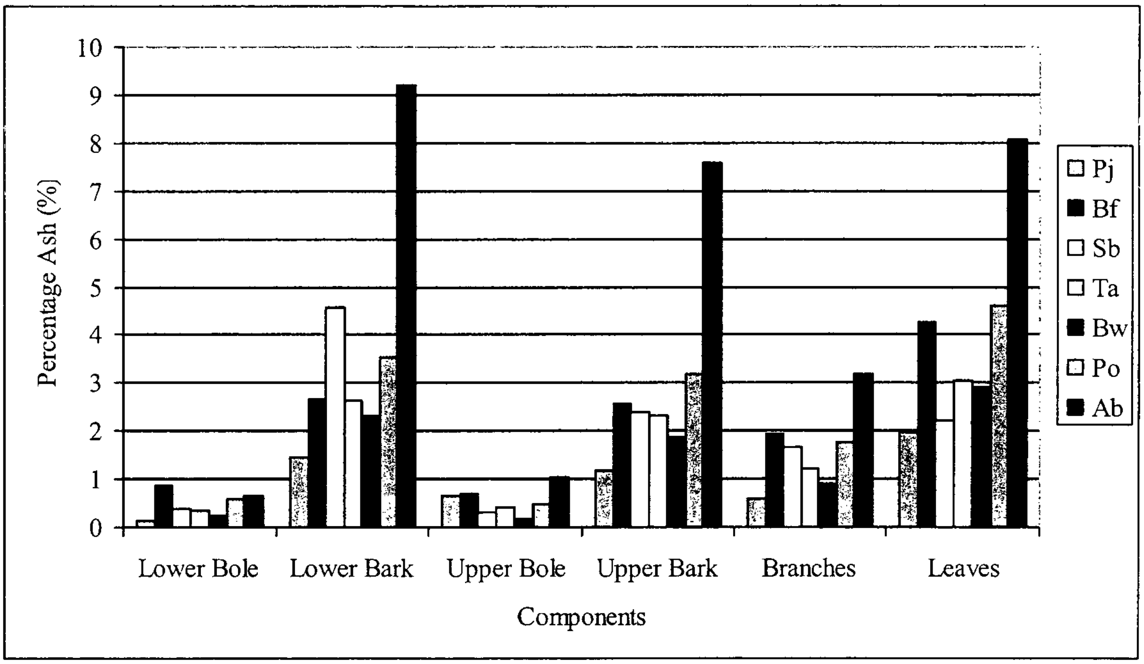
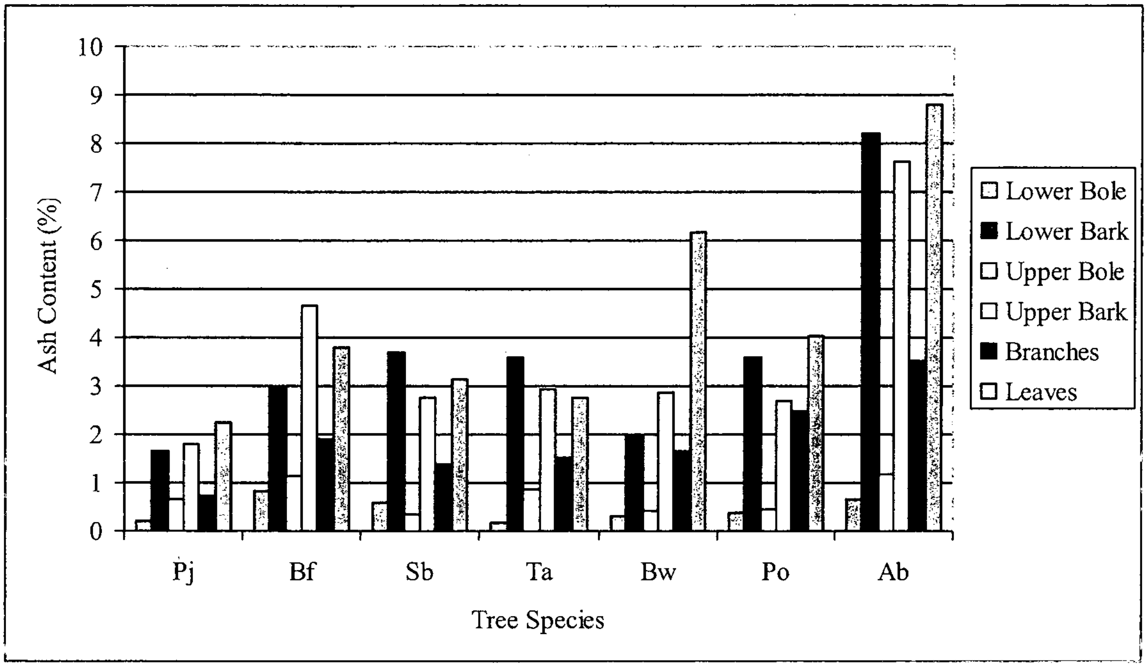


Figure 15. Interactions between the percentage ash content of species and component treatments at the Thunder Bay site with both represented on the x-axis.



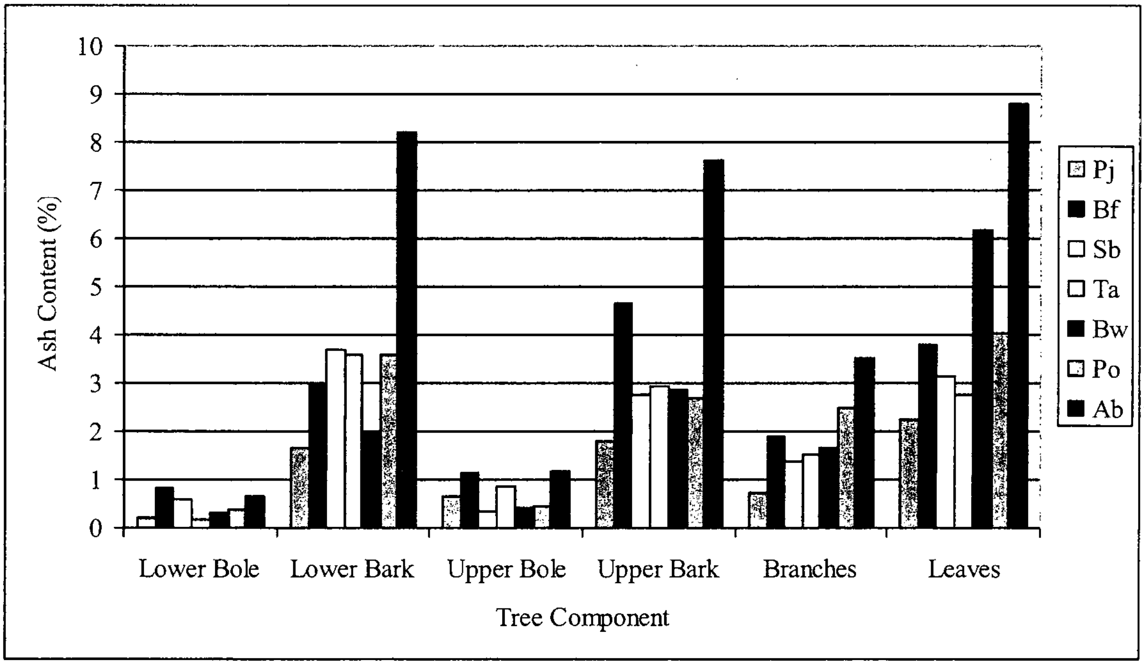
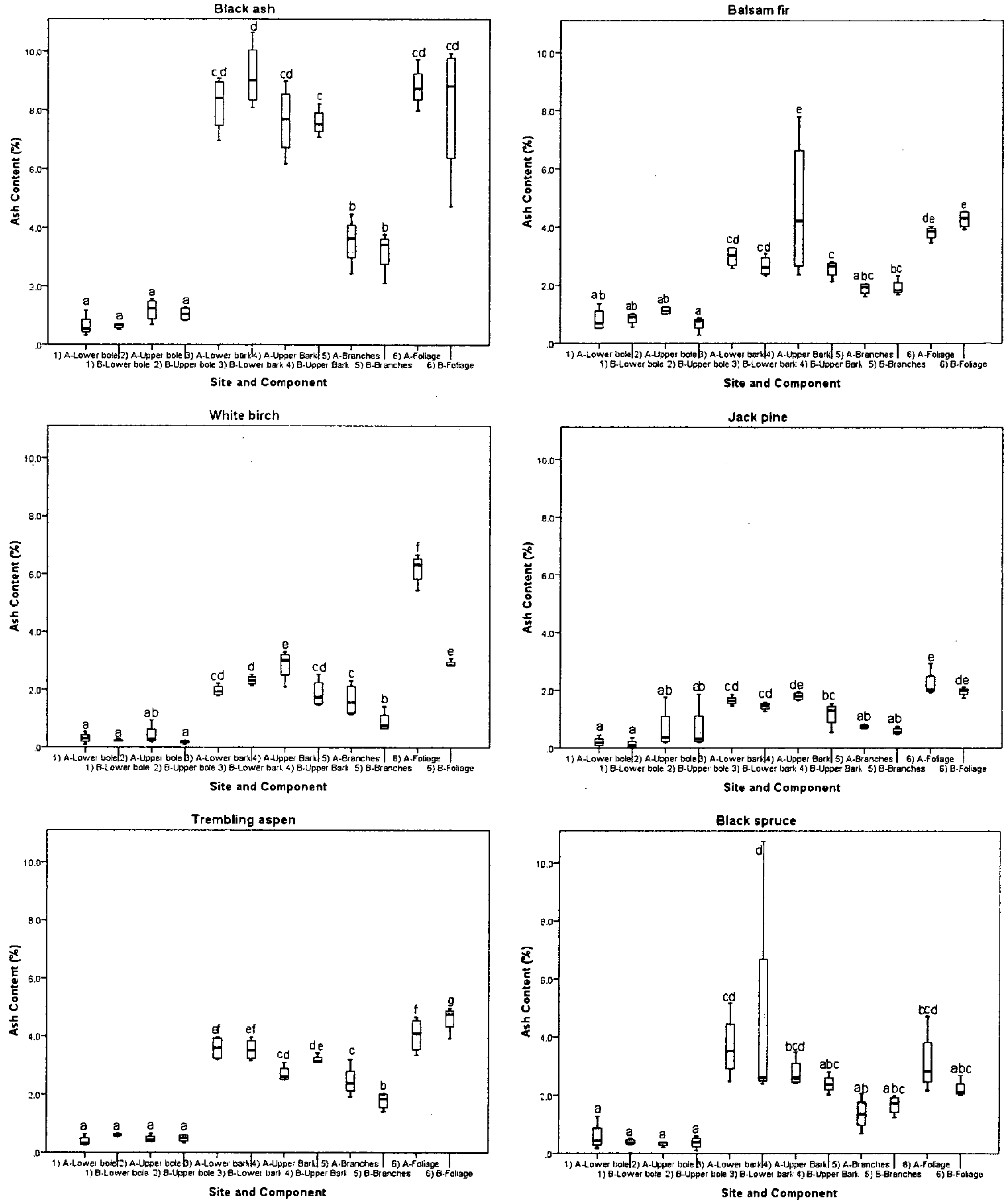


Figure 16. Interactions between the percentage ash content of species and component treatments at the Atikokan site with both represented on the x-axis.

Box plots were used to further explore the species-component-site interaction this was plotted with both species and components on the x-axis (Figure 17, Figure 18). Duncan's test was used to provide groupings within treatment sets. Using Duncan's test certain trends through the different species (Figure 17) are now apparent. For every species lower bole and upper bole were grouped together and these groups did contain other components at times. There were also tendencies to group lower bark, upper bark and foliage together but was not as distinct as the groupings found for wood.

For components there were no real trends present (Figure 18). From the boxplots we can see that each component has very different groupings. In the lower and upper bole components we see much lower ash content and much less variability then the other components and were grouped together in a few overlapping groups. The other four components have much more variability and the groupings are fairly specific with the exception of black ash which is grouped together with the highest ash content.



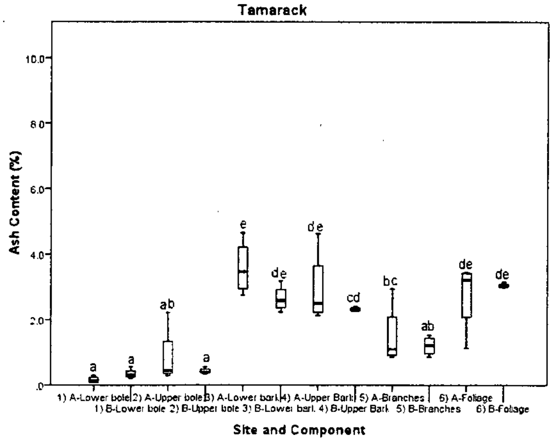


Figure 17. The three way interaction of the percentage ash content of specie, site and components with different graphs for each component. The site is indicated on the x-axis by an "a" (Atikokan) or "b" (Thunder Bay). Letters above each boxplot indicate groups of components within a species from Duncan's test. Similar letters indicate no significant difference.

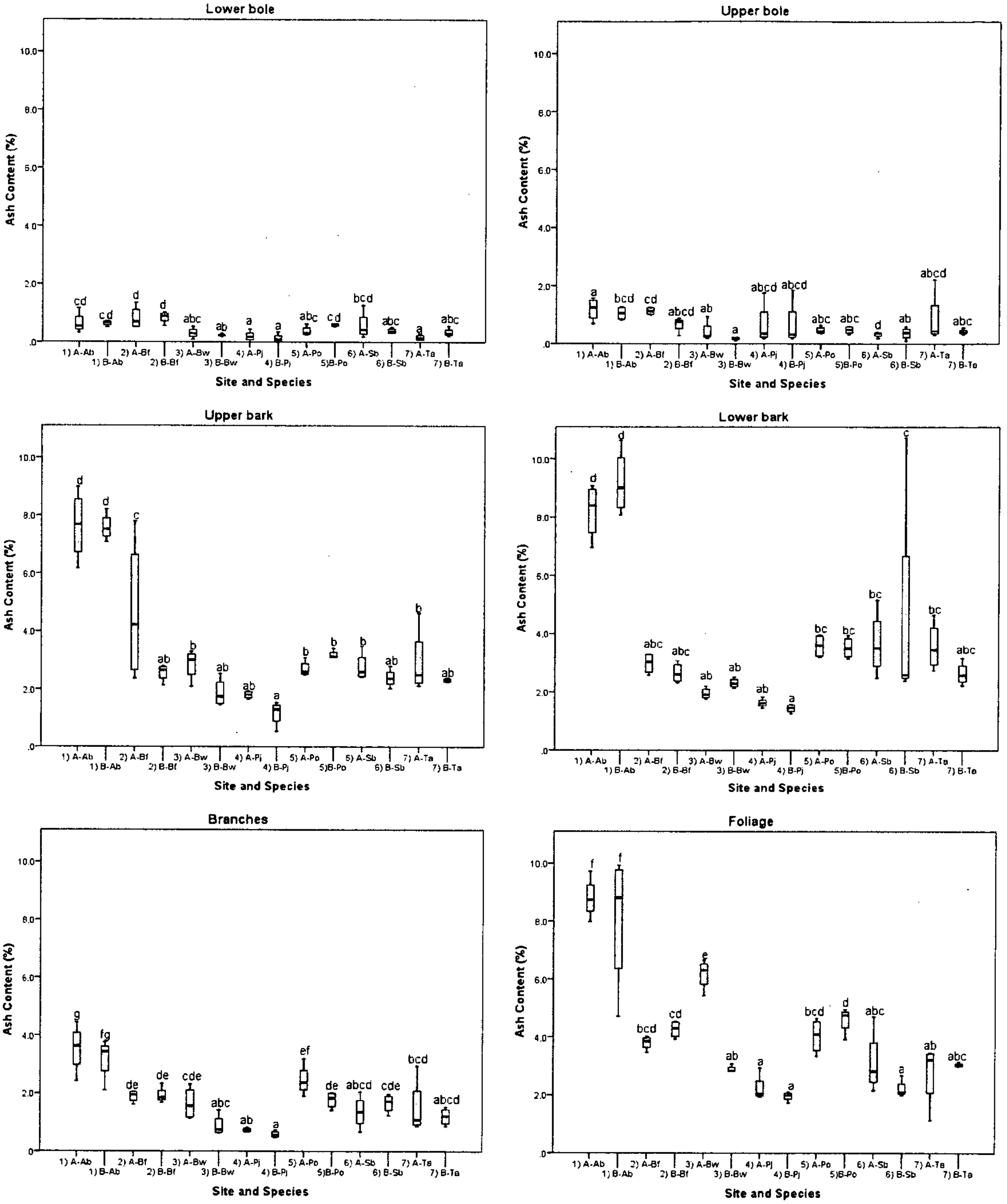


Figure 18. The three way interaction of percentage ash content of component, site and species with a different graph for each component. The site is indicated on the x-axis by an "a" (Atikokan) or "b" (Thunder Bay). Letters above each boxplot indicate groups of species within a component from Duncan's test. Similar letters indicate no significant difference.

4.4 DISCUSSION

The objectives of this chapter, to investigate the ash content of different tree species and their components at different sites, were completed. This knowledge can now be applied to the management of biomass to help ensure ash content does not exceed boiler tolerances. This database can be used in northwestern Ontario to combine high ash content feedstock with low ash content feedstock for an average acceptable in boilers.

A significant difference of ash content was found between the sites, species and components sampled. The two sites sampled were found to be significantly different which comes as no surprise as ash content is influenced by soil type, drainage, climate and many other site characteristics (Hakkila 1989, Demeyer et al. 2001). Although these two sites were found to be significantly different each situation requiring biomass must be evaluated to determine whether the increase at the Atikokan site is enough to disrupt the operations of the boiler. Tree species was also found to be significantly different which was also expected because of the tendency of trees to grow in different micro sites within a cut block as well as contain different cell types. The largest difference in tree species is due to the varying amount of parenchyma cells which contain large amounts of calcium (Panshin and DeZeeuw 1980). The highest amounts of parenchyma cells were expected to be in the ring porous hardwood, black ash, which did have much higher ash contents. The lowest ash content was expected to be softwoods due to their low amount of parenchyma cells (Panshin and DeZeeuw 1980) but were not shown to be in their own distinct groups for any components (Figure 18). Ash content may also be the reason for the low calorific value of black ash as the increased amount of non-combustibles lowers the available energy of biomass (Cassida et al. 2005, Monti et al.

2008). Tree component was also found to be statistically different and was more than expected as the different components of the tree have drastically different amounts of ash content (Hakkila 1989). On average foliage was found to have the highest ash content, 4.15%, but the lower bark contained the highest amount measured, 9.18%. The ash content for the wood components were the lowest which averaged 0.45% and 0.63% for the lower and upper boles respectively. The increased ash content from the lower to upper bole could be explained by the amount of reaction wood in the upper parts of the tree, which produces higher amounts of ash (Panshin and DeZeeuw 1980, Hakkila 1989) With such low ash content in wood it will easily lower the average ash content of biomass feedstock especially considering wood is the most abundant part of a tree. The complexity of the 3-way interaction for ash content confirms the literature of the importance of site, species, and component. This complexity causes difficulties to see trends when the 3-way interactions are examined (Figure 17 and Figure 18) but it is apparent that the wood (both lower and upper bole) is grouped together for each species and is lower and more consistent than the other components.

Although there is limited literature on the ash content of Canadian tree species and their component comparisons to other tree species in other areas of the world is useful. Wood was found to have consistent and low ash content (Hakkila 1989) and this study agrees with those findings. Hakkila (1989) found that stem wood ash content in softwoods and hardwoods were 0.3±0.1% and 0.5±0.3% respectively. This is similar to the results of this study which found the stem wood of softwoods and hardwoods to average 0.53% and 0.55%, respectively. Bark and foliage results also seem to correspond with published data as well, bark averaged 3.51% and foliage averaged

4.15% slightly higher than 2.97% for bark but lower than 4.97% for foliage in five Finnish Species (Hakkila 1989).

CHAPTER 5

FUEL QUALITY OF FIRE KILLED TREES

5.1 INTRODUCTION

As the need for biomass increases, harvesting residues may no longer satisfy the needs of cogeneration facilities and new sources may be sought after. A potential source of woody biomass in Ontario is from forest fires. On average, an area of 122,190 ha or over 1 million m^3 of wood is devastated by wildfire every year in Ontario and has the potential to be salvaged (OMNR 2008). Although there have been concerns raised on the effects of salvage logging on the natural ecosystem (Nappi et al. 2004) the current forest management regime in Ontario "… has been to encourage utilization of fired killed and damaged trees … where appropriate" (OMNR 2002). The salvage of fire killed trees has been identified as an important source of fibre for the pulp and paper industry as well as other forest sector industries in Canada but these endeavours may not be the most profitable option in today's economic climate. Chip charcoal content, mechanical pulp brightness and low chip moisture content are major concerns (Watson and Potter 2004). Chip charcoal content and mechanical brightness can be regulated by aggressive debarking. Chip moisture content can be controlled by harvest within one year of the fire. Similarly Moya et al. (2008) found that fire killed trees produced oriented strand board within industrial standards but wood was harvested within three weeks of the fire and the amount of charred material was controlled. With most products demanding a narrow time frame for harvest and the added difficulties of sorting fire burnt trees for proper use, it allows less demanding uses such as heat and energy production to be a more feasible use of the timber.

Fired killed ponderosa pine (*Pinus ponderosa* Dougl. Ex laws.) have been recognized as a high quality source of biomass in Colorado for energy production due to its' low moisture content and similar energy content to unburnt trees (Mackes and Jennings 2008). This research, although relevant, is difficult to apply to Ontario due to having different tree species as well as drastically different climate. The fuel quality of wildfire areas for bioenergy production in northern Ontario has not been investigated but is a promising source of biomass for energy production. To begin assessing the viability of recovering biomass from burnt trees a study has been conducted to assess the quality of fuel from standing trees left after a burn in the area surrounding Thunder Bay.

This study will look at two important fuel characteristics, moisture content and calorific values. Moisture content has extremely detrimental effects to the production and use of biomass for energy as described in section 1.2.5. These two characteristics will be tested across four of the most prominent boreal tree species; white birch, trembling aspen, balsam fir and black spruce. These species compose 70% of the forested area in Ontario and 70% of the annual cut in 2004/2005, making their importance and abundance quite apparent (OMNR 2008). This will be repeated in five different fires of increasing ages since fire to begin understanding the possibility of timed harvests to maximize fuel quality.

5.2 METHODOLOGY

5.2.1 Study Area

Five forest fires of different ages were identified within the Thunder Bay MNR District with help from Abitibi-Bowater and the OMNR. The five fires were 12, 18, 24, 37 and 52 months old and are identified and described in Table 10. Site locations are shown in Figure 19. These five fires were selected due to their proximity to Thunder Bay as well as their representation of five different time periods since timber was left standing dead from fire.

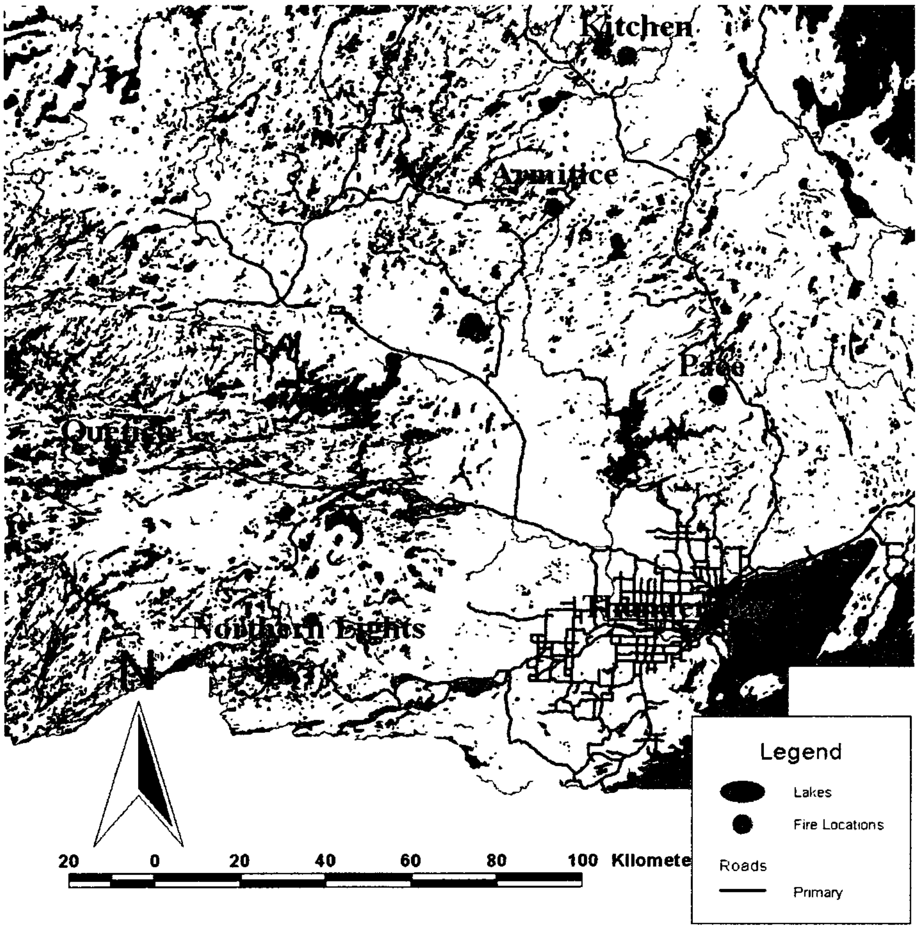


Figure 19. Locations of five forest fire sample sites.

Table 10. General Information on the five study fires.

Fire Name	Month of Fire	Months Since Fire	Location of Fire	Brief Description
Pace	July, 2007	12	Near Pace Lake off of Hwy. 527 around km 40.	• Bark still on all trees • Mix of Upland and Lowland areas • Mainly younger trees • Small regen when present• Only fallen trees on fire edge
Northern Lights	May, 2007	18	South of Northern Lights Lake down Trout Bay Rd. towards Border. Around 140 km West from Thunder Bay.	• Bark still on trees • Some areas of intense burn • Most burnt areas are 30 year old plantations • Some Po bark has begun peeling and splitting • Almost no regen due to age of burnt trees • Only fallen trees on fire edge
Kitchen	July, 2006	24	Off of the Kitchen Rd. off of Hwy. 811. Around 150 km North from Thunder Bay.	• Most Po have bark splitting or peeling • Small regen present in large amounts • Older stand with the ability to seed in after fire • Fallen trees mainly on fires edge
Armitice	June, 2005	37	Off of Hwy. 811. Around 150 km North from Thunder.	• Bark has peeled off of some Po and begun on Bw • Rocky Upland site • Mature trees • Site has regen up to a half meter tall • Fallen trees on fires edge and some throughout
Quetico	June, 2004	52	At the Dawson trail campground at French Lake in Quetico Provincial Park. Around 180 km west from Thunder Bay.	• Some bark off of Po and Bw • Regen shoulder height although mostly Po • Many downed trees possibly from a combination of age of fire and water bombers.

5.2.2 Field Sampling

Each of the four tree species selected was sampled for calorific value and moisture content at each fire. An example of a fire site is pictured in Figure 20. The moisture content was sampled in the field using a Protimeter Surveymaster SM. The calorific values were tested in the laboratory from collected samples to ensure that the findings of Mackes and Jennings (2008) have similar energy content to unburnt trees applies to northwestern Ontario tree species. Only one tree per species per site was sampled for calorific value and although no statistical test is preformed this information should reveal any concerning decreases in calorific values.

Figure 20. Picture of the Armistice Fire site. Source: Hosegood 2008.

5.2.2.1 Moisture Content

The same sampling procedures were used for all fire sites as there were no constraints due to forest harvesting operations. The trees chosen at each of the fires followed the same sampling criteria. All samples trees had minimal amounts of fire scarring: i.e., fire penetration no deeper than the bark. Every attempt was made to sample mature trees when they are present at the fire, although at the Northern Lights and Pace Lake fires there were limited mature trees to choose from. At each fire a total of seven trees of each species were assessed for their moisture content. To assess the moisture content of the sample trees, bark was removed along with 1 cm of wood with an axe at 1.3 m. The Protimeter Surveymaster SM was then used to obtain the moisture content of the tree and the value was recorded. This was repeated seven times at random in each of the four species.

5.2.2.1 Calorific values

At each fire site there was a sample taken from each of the four tree species to determine the calorific value of the trees. This sample tree was chosen from the seven trees chosen for moisture content determination. Of these seven trees the most representative tree of the site was chosen and a bolt was cut from 1.3 m and then placed in sample bags for transport back to the laboratory. These samples were then tested for calorific value.

5.2.3 Sample Preparation

Samples were prepared in the same fashion outlined in section 2.2.3 for round wood.

5.2.4 Determination of Calorific Values

The procedures outlined in section 2.2.4 were followed.

5.2.5 Statistical Analysis and Experimental design

This experiment was designed to test the hypotheses that, fire age and tree species affect moisture content. This study's selected sites and tree species were all outlined in section 5.1and 5.2 and will be used as factors in an ANOVA test. Calorific values are not tested statistically. The General Linear Model Method in SPSS will be used to test the following null hypotheses:

H1: Fire age does not affect moisture content of fire burnt trees.

H2: Tree species does not affect moisture content of fire burnt trees.

The linear model used to explain the experimental design is a full factorial design with the experimental units being each moisture reading of a tree. With seven repetitions of each of the four tree species at each of the five sites the experimental size is 140. The linear model for this experiment is as follows in equation 9:

$$Y_{ijk} = \mu + F_i + S_j + FS_{ij} + \epsilon_{(ij)k} \qquad [9]$$

$i = 1,2,3,4,5 \quad j = 1,2,3,4 \quad k = 1,2,3,4,5,6,7$

Where,
Y_{ijk} = the moisture content value of the k^{th} replicate, j^{th} species and i^{th} fire age.
μ = the grand mean.
F_i = the fixed effect of the i^{th} of five levels of fire age.
S_j = the fixed effect of the j^{th} of four levels of tree species.
FS_{ij} = the interaction effect of i^{th} fire age with j^{th} tree species.
$\epsilon_{(ij)k}$ = the random effect of k^{th} repetition within the i^{th} fire age and j^{th} species.

5.3 RESULTS

The data collected from the field with the protimeter, which is presented in appendix 4 and summarized in Table 11, was analysed using two statistical methods ANOVA and Duncan's test. All raw calorific values data is presented in Table 11. ANOVA was run to test if the two null hypotheses will be rejected. Following the ANOVA, Duncan's test was run to explore if certain species and components could be grouped into similar subsets within significant terms. The data set was found to have grand mean of 30.08% moisture content, with a standard deviation of 14.65%. The maximum value, which occurred in trembling aspen at the 12 month old fire, was 53.69%, the minimum value, which occurred in black spruce at the 24 month old fire and was 16.81%. For a species as a whole the highest average moisture content was found to be white birch with 41.34% and the lowest was black spruce with 20.26%.

The ANOVA results are presented in Table 12. Table 12 shows that significant differences were found for the two treatments. A significant difference was found for the 2-way interaction between species and fire age. The level of significance is indicated in Table 12. The interaction between fire age and tree species is illustrated in Figure 21.

Table 11. Moisture content and calorific content for studied species and fire ages.

Average Moisture Content (%)				
	Tree Species			
Months	Balsam fir	White birch	Trembling aspen	Black spruce
12	26.75	45.56	53.69	22.50
18	22.85	43.67	34.22	21.82
24	17.67	40.88	49.17	16.81
37	18.71	38.99	26.28	17.24
52	22.57	37.62	39.70	22.95

Calorific Value (MJ/kg)				
	Tree Species			
Months	Balsam fir	White birch	Trembling aspen	Black spruce
12	20.54	19.59	19.19	20.08
18	20.97	20.00	19.65	20.54
24	19.97	19.24	19.02	19.37
37	19.96	19.25	19.04	19.69
52	20.02	19.56	19.36	19.62

Table 12. Anova results for moisture content.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Species	14032.718	3	4677.573	48.923	***
Months	1964.985	4	491.246	5.138	**
Species*months	2393.214	12	199.435	2.086	*
Error	11473.239	120	95.610		
Total	164247.568	139			

* = significant at α=0.05.
** = significant at α=0.01.
*** = significant at α=0.001.
ns = not significant

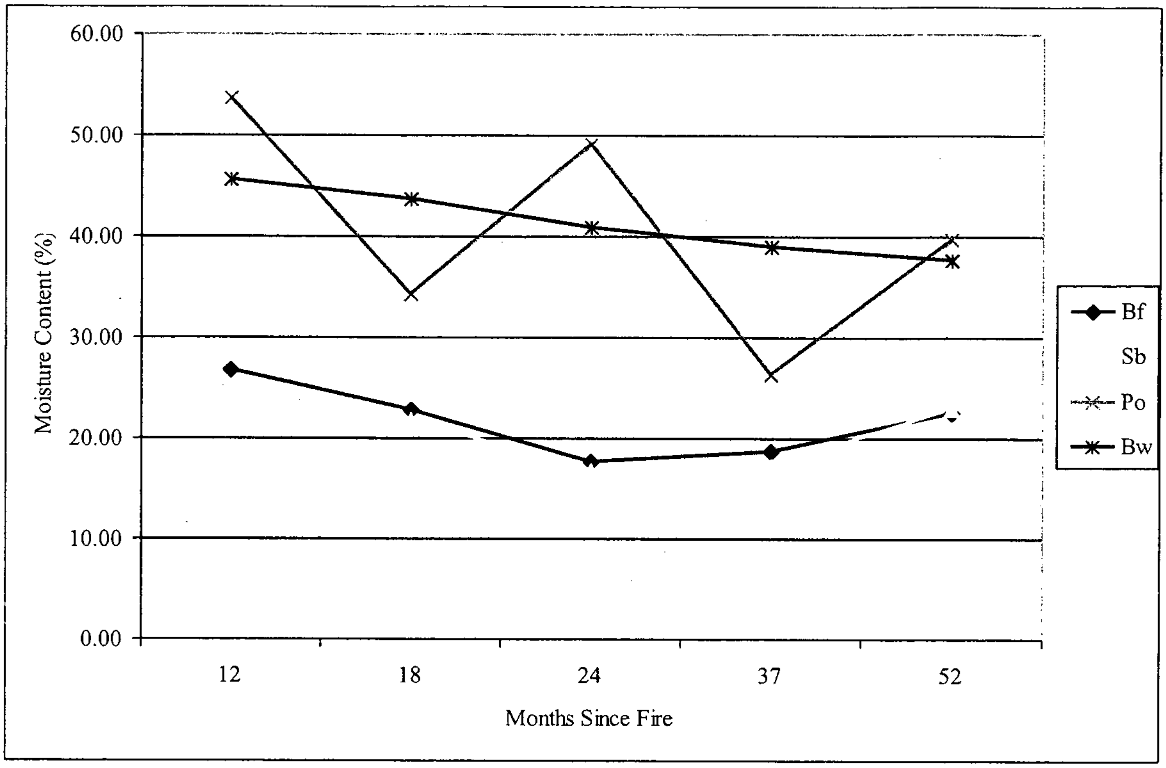


Figure 21. Moisture content of the four tree species at the five different fire ages.

Box plots were used to further explore the species-fire age interaction this was plotted against moisture content (Figure 22). Duncan's test was used to provide groupings within the treatment set. Using Duncan's test certain trends through the different species (Figure 22) are now apparent. All softwoods were grouped together in group "a" with only one hardwood present in that group. Although there is some overlap between the groups containing the hardwoods there seems to be two fairly separated groups between hardwood and softwood trees.

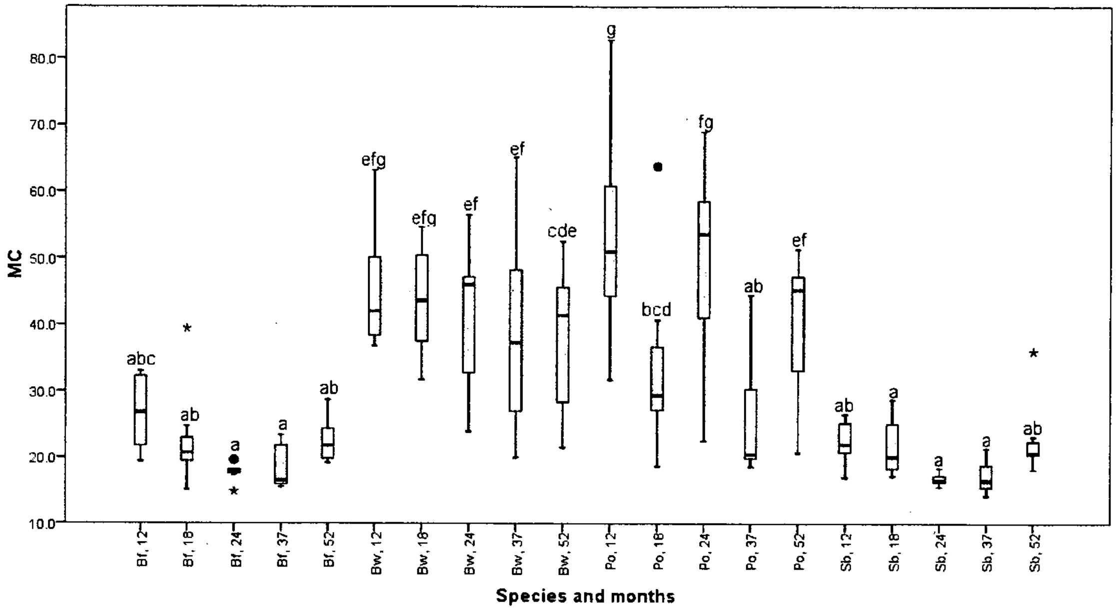


Figure 22. The species-fire age interaction plotted against moisture content. Similar letters indicate groups from Duncan's test. Similar letters mean no significant difference.

5.4 DISCUSSION

The general trend was a decrease in moisture content over time although a gradual increase in moisture content appeared in the oldest fires. These findings are consistent with those of Mackes and Jennings (2008), who found that in a seven year old fire moisture content in Ponderosa Pine was reduced to 9.4% compared to 77.8% in living trees. Similar finding to Mackes and Jennings (2008) were also found for caloric value of fire burnt trees. As shown in Table 11 calorific value of wood from fire sample sites were similar to previously published calorific values (Table 1). The average calorific value in this study found for lower bole wood of white birch, trembling aspen, jack pine and balsam fir was 19.7MJ/kg (Table 3) and in Table 11 was 19.7MJ/kg. Unfortunately with no repetitions at each of the fires no statistical comparison can be preformed. Even without statistical analysis the equal values found in the living and dead trees does lend itself to show that there are no drastic changed in calorific content of tree following a fire disturbance.

The use of fire killed trees as a source of biomass is a feasible option based on its moisture content of 30.98% on average. The most crucial piece of information discovered was the inherent moisture content difference between the hardwood and softwood trees. Hardwood trees had an average of 40.98% moisture content which was 20% higher than the moisture content of softwood trees averaging 20.98%. The extreme variation found in many cases of hardwood trees could partially cause by the protimeter used to conduct field sampling. As moisture content increases in a sample the accuracy of the protimeter decreases. These two distinct groups will allow proper sorting and mixing of different tree species to control the moisture content of feedstock entering a boiler. It seems apparent that softwood trees dry quickly after fire and quickly approach the equilibrium moisture content in the area of approximately 14% (Simpson 1998). The bark remaining on the trees following a fire may be one on the major factors effecting moisture content as it has been found that logs without bark can dry up to three times quicker than logs with bark (Defo and Brunette 2006). Softwoods may quickly reduce their moisture due to the observed splitting and shedding of bark which exposes wood and increases drying. Hardwoods on the other hand seem to slowly decrease in moisture content after a fire and bark remained on the trees until older fires where only some trees had shed their bark.

Timing a salvage cut may be the most difficult decision for forest managers wanting to acquire biomass from fire killed trees. Figure 21 and Figure 22 do not provide very useful information surrounding the lowest moisture content of fire burnt trees as there are fluctuations throughout different fire ages and do not necessarily show a decreasing trend. Figure 22 also groups the fires into subsets which are not useful operationally. Through these confusing results one conclusion can be drawn, timing of salvage harvest may not be a useful planning consideration. Waiting for fire burnt trees to reach their driest point may not be the best option for forest managers. Many boreal tree species depend heavily on forest fires to provide proper germination sites for seeds released after the fire and begin seeding in sites shortly after a fire take place (OMNR 2002). The longer the period of time after the fire the larger the seedling on site which can be damaged by the harvesting operations. To reduce the amount of seedling damage salvage operations can be treated as a shelterwood cut. By implementing shelterwood operations planning of the harvest skidways, timing of year and specialized equipment can be used to maximize profits and minimize site damage (Hanell et al. 2000). Fire sites were also found to have increasing amount of fallen timber on the site in older fires.

Although trees on the ground may be harvested for biomass it is unknown if these trees would have as low of moisture content as was found in the dead standing timber.

Salvage logging of fire killed areas can also be used as a site rehabilitation technique. An example of this is the Northern Lights site where the fire occurred mainly in young plantations of jack pine which do not yet have many seeds banked in the canopy to be released after fire (Farrar 1999). With this site not having the ability to naturally regenerate itself and it being difficult to replant due to dead standing timber being an obstruction as well as a hazard to tree planters, biomass harvesting may be fitting. Removal of the dead standing timber at the Northern Lights burn could be a profitable exercise and allow the reestablishment of the killed plantations.

CHAPTER 6

CONCLUSIONS

6.1 CONCLUSIONS

Increasing efficiency has been demanded of many industries including the forestry sector. In the present market situation and minimal profits to waste there is decreasing room for errors while managing a forest. While branching into the new bioenergy sector, it is important to keep this venture as efficient as possible by extensive planning. This information of fuel characteristics of seven northwestern Ontario tree species provided by this study can allow the proper planning and estimates of forest harvesting residues. This study has also shown that the fuel characteristics in northwestern Ontario are conducive to supporting a profitable bioenergy sector. Calorific value, specific gravity and ash content of northwestern Ontario's trees have all been shown to be superior than previously published data. Previous data also had many inadequacies due to information lacking for certain species and components which were completed by this study. This study was successful in determining significant differences between tree species, components, and site for Calorific value, specific gravity and ash content. Similarities between components at species were also shown and will be useful when broad biomass harvesting occurs.

6.2 MANAGEMENT SCENARIO

To illustrate the application of this data and the benefits to area specific information a scenario is created. This scenario was run twice once with the data found by this study and again by previously published data, which are then compared. The context of this scenario is for the residues after a harvest of a mixedwood stand. This stand is composed mainly of jack pine but also contains balsam fir and trembling aspen. The jack pine and balsam fir is harvested for structural lumber as well as pulp and Trembling aspen is harvested for pulp and veneer logs. The remaining percentages left as residues are all educated guesses to reflect the components and species left at this site. However, these numbers do not affect the goal of this scenario, which is to demonstrate where the results from this study can be used and highlight the differences between previously published data and the results of this study. This scenario assumes that the harvesting residues are left on site to dry and allow leaching of nutrients and defoliation to take place (Nurmi 1999). The scenario assumes that the amount of foliage left is negligible and is presented in Table 13.

The management scenario in Table 13 clearly demonstrates the differences in previously published data to the results of this study. The shortcomings of information from many different areas and gaps in this information become extremely apparent once a larger scale scenario is used. On a per truck load basis (Table 13), the estimated energy content using previously published data is 35% lower than using this study's results. Ash content did change on a per truck load basis but as a percent only increased from 1.33% to 1.42%. The criterion with the largest impact on the scenario was specific gravity, using different values for each component drastically increased energy estimates in scenario 1. In scenario 2, the wood specific gravity of each species is used for each component as it is the only reference to use. Using the wood specific gravity for the bark and branch components underestimates the density of the harvesting residues. This management scenario has also helped in finding limitations to this study and recommendations of future work.

Table 13. Management Scenario of harvesting residue fuel characteristics.

Scenario 1, Data From This Study			
		Species	
Tree Component	Jack Pine	Balsam Fir	Trembling Aspen
Lower Bole	5.0%	5.0%	30.0%
Lower Bark	2.5%	2.5%	15.0%
Upper Bole	25.0%	25.0%	20.0%
Upper Bark	12.5%	12.5%	10.0%
Branches	55.0%	55.0%	25.0%
% of all Residues	42.0%	17.0%	41.0%
Calorific Value (MJ/kg)	20.86	20.79	20.54
Ash Content	0.802	1.982	1.602
Specific Gravity	0.566	0.593	0.566
Total Energy Per Truck (MJ)		590921.7	
Total Ash Content Per Truck (kg)		379.5	
Scenario 2, Previously Published Data			
		Species	
Tree Component	Jack Pine	Balsam Fir	Trembling Aspen
Lower Bole	5.0%	5.0%	30.0%
Lower Bark	2.5%	2.5%	15.0%
Upper Bole	25.0%	25.0%	20.0%
Upper Bark	12.5%	12.5%	10.0%
Branches	55.0%	55.0%	25.0%
% of all Residues	42.0%	17.0%	41.0%
Calorific Value (MJ/kg)	20.61	19.69	19.19
Ash Content (%)	1.372	1.705	1.373
Specific Gravity	0.400	0.350	0.380
Total Energy Per Truck (MJ)		380793.8	
Total Ash Content Per Truck (kg)		273.8	

Source: Appendix 1, Appendix 2, Appendix 3, Table 1, Table 2

6.3 LIMITATIONS AND FUTURE WORK

Although the information acquired by this study is extremely useful for the bioenergy sector there are limitations to this data. To properly apply this data there is still a great amount of information which should be collect and was apparent in the management scenario. The limitations of this study and recommended future work are;

- Although there were different area sampled in this study, it is important to not over extend the inference space of this study. A broader geographical study in the area may be necessary to classify all or northwestern Ontario and limit the problems which were found when using data from other areas.
- Only seven tree species were studied due to limited time and resources but studying other species which are present in the area should be completed.
- Only six tree components were chosen to immediately flow into bioenergy sector but it may become necessary to increase accuracy and break down these components into smaller more distinct groups.
- Trees were cut from the living state and the testing begun as quickly as possible to limit variability of the samples. This could become a problem as most harvesting residue is left at the harvesting site for a long period of time, which could introduce rot and leaching. A study of harvesting residue over time could help in understanding how fuel quality is affected by time.
- The removal of harvesting residues from a site could have a negative impact on the site by removing nutrients. Research into the negative affects of the removal of harvesting residues should be done to reduce any possible harm.

- To provide more accurate estimates of energy available from harvesting residues, research needs to be done in the biomass available at the site. Although Lambert et al. (2005) has created equations for the total amount of above ground biomass it is not completely applicable to this situation. Different harvesting techniques and end use of trees will dictate the harvesting waste left on a site and therefore the total amount of energy.

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APPENDICES

APPENDIX 1
CALORIFIC VALUES RAW DATA

Site	Species	Component	MJ/Kg
Thunder Bay	Ab	Lower bole	19.309
Thunder Bay	Ab	Lower bole	19.517
Thunder Bay	Ab	Lower bole	19.141
Thunder Bay	Ab	Lower bole	18.854
Thunder Bay	Ab	Lower bark	18.969
Thunder Bay	Ab	Lower bark	18.703
Thunder Bay	Ab	Lower bark	18.145
Thunder Bay	Ab	Lower bark	17.588
Thunder Bay	Ab	Upper bole	19.462
Thunder Bay	Ab	Upper bole	19.995
Thunder Bay	Ab	Upper bole	19.016
Thunder Bay	Ab	Upper bole	19.174
Thunder Bay	Ab	Upper bark	19.247
Thunder Bay	Ab	Upper bark	19.235
Thunder Bay	Ab	Upper bark	18.510
Thunder Bay	Ab	Upper bark	18.410
Thunder Bay	Ab	Branches	20.644
Thunder Bay	Ab	Branches	19.581
Thunder Bay	Ab	Branches	19.059
Thunder Bay	Ab	Branches	19.256
Thunder Bay	Ab	Foliage	19.505
Thunder Bay	Ab	Foliage	19.727
Thunder Bay	Ab	Foliage	19.044
Thunder Bay	Ab	Foliage	19.170
Thunder Bay	Bf	Lower bole	19.797
Thunder Bay	Bf	Lower bole	19.763
Thunder Bay	Bf	Lower bole	20.105
Thunder Bay	Bf	Lower bole	19.875
Thunder Bay	Bf	Lower bark	21.158
Thunder Bay	Bf	Lower bark	21.019
Thunder Bay	Bf	Lower bark	20.960
Thunder Bay	Bf	Lower bark	21.396
Thunder Bay	Bf	Upper bole	19.949
Thunder Bay	Bf	Upper bole	20.547
Thunder Bay	Bf	Upper bole	19.775
Thunder Bay	Bf	Upper bole	19.597
Thunder Bay	Bf	Upper bark	21.692
Thunder Bay	Bf	Upper bark	21.258
Thunder Bay	Bf	Upper bark	21.223
Thunder Bay	Bf	Upper bark	22.779
Thunder Bay	Bf	Branches	21.545
Thunder Bay	Bf	Branches	20.124
Thunder Bay	Bf	Branches	20.240
Thunder Bay	Bf	Branches	19.981
Thunder Bay	Bf	Foliage	22.581

Thunder Bay	Bf	Foliage	22.284
Thunder Bay	Bf	Foliage	22.493
Thunder Bay	Bf	Foliage	22.908
Thunder Bay	Bw	Lower bole	18.975
Thunder Bay	Bw	Lower bole	19.103
Thunder Bay	Bw	Lower bole	20.645
Thunder Bay	Bw	Lower bole	20.392
Thunder Bay	Bw	Lower bark	24.238
Thunder Bay	Bw	Lower bark	25.063
Thunder Bay	Bw	Lower bark	24.129
Thunder Bay	Bw	Lower bark	24.726
Thunder Bay	Bw	Upper bole	19.239
Thunder Bay	Bw	Upper bole	19.388
Thunder Bay	Bw	Upper bole	20.553
Thunder Bay	Bw	Upper bole	19.880
Thunder Bay	Bw	Upper bark	22.785
Thunder Bay	Bw	Upper bark	23.919
Thunder Bay	Bw	Upper bark	25.192
Thunder Bay	Bw	Upper bark	26.647
Thunder Bay	Bw	Branches	21.397
Thunder Bay	Bw	Branches	20.594
Thunder Bay	Bw	Branches	20.083
Thunder Bay	Bw	Branches	20.691
Thunder Bay	Bw	Foliage	21.226
Thunder Bay	Bw	Foliage	20.902
Thunder Bay	Bw	Foliage	20.976
Thunder Bay	Bw	Foliage	21.300
Thunder Bay	Pj	Lower bole	20.155
Thunder Bay	Pj	Lower bole	19.182
Thunder Bay	Pj	Lower bole	19.437
Thunder Bay	Pj	Lower bole	19.457
Thunder Bay	Pj	Lower bark	21.200
Thunder Bay	Pj	Lower bark	21.863
Thunder Bay	Pj	Lower bark	21.109
Thunder Bay	Pj	Lower bark	22.152
Thunder Bay	Pj	Upper bole	19.975
Thunder Bay	Pj	Upper bole	19.254
Thunder Bay	Pj	Upper bole	19.567
Thunder Bay	Pj	Upper bole	20.119
Thunder Bay	Pj	Upper bark	20.753
Thunder Bay	Pj	Upper bark	20.503
Thunder Bay	Pj	Upper bark	21.163
Thunder Bay	Pj	Upper bark	21.613
Thunder Bay	Pj	Branches	20.234
Thunder Bay	Pj	Branches	19.852
Thunder Bay	Pj	Branches	20.201
Thunder Bay	Pj	Branches	20.797
Thunder Bay	Pj	Foliage	22.374
Thunder Bay	Pj	Foliage	22.513
Thunder Bay	Pj	Foliage	22.589

Thunder Bay	Pj	Foliage	22.327
Thunder Bay	Po	Lower bole	19.422
Thunder Bay	Po	Lower bole	20.135
Thunder Bay	Po	Lower bole	19.800
Thunder Bay	Po	Lower bole	19.354
Thunder Bay	Po	Lower bark	22.573
Thunder Bay	Po	Lower bark	22.652
Thunder Bay	Po	Lower bark	22.390
Thunder Bay	Po	Lower bark	21.380
Thunder Bay	Po	Upper bole	19.647
Thunder Bay	Po	Upper bole	19.835
Thunder Bay	Po	Upper bole	19.657
Thunder Bay	Po	Upper bole	19.208
Thunder Bay	Po	Upper bark	21.828
Thunder Bay	Po	Upper bark	21.644
Thunder Bay	Po	Upper bark	21.665
Thunder Bay	Po	Upper bark	21.158
Thunder Bay	Po	Branches	20.411
Thunder Bay	Po	Branches	21.196
Thunder Bay	Po	Branches	22.087
Thunder Bay	Po	Branches	20.435
Thunder Bay	Po	Foliage	21.927
Thunder Bay	Po	Foliage	21.766
Thunder Bay	Po	Foliage	21.704
Thunder Bay	Po	Foliage	21.326
Thunder Bay	Sb	Lower bole	19.313
Thunder Bay	Sb	Lower bole	18.949
Thunder Bay	Sb	Lower bole	19.285
Thunder Bay	Sb	Lower bole	19.192
Thunder Bay	Sb	Lower bark	20.491
Thunder Bay	Sb	Lower bark	20.231
Thunder Bay	Sb	Lower bark	20.350
Thunder Bay	Sb	Lower bark	21.250
Thunder Bay	Sb	Upper bole	19.341
Thunder Bay	Sb	Upper bole	19.187
Thunder Bay	Sb	Upper bole	19.301
Thunder Bay	Sb	Upper bole	19.207
Thunder Bay	Sb	Upper bark	20.162
Thunder Bay	Sb	Upper bark	20.161
Thunder Bay	Sb	Upper bark	20.474
Thunder Bay	Sb	Upper bark	20.160
Thunder Bay	Sb	Branches	21.542
Thunder Bay	Sb	Branches	22.112
Thunder Bay	Sb	Branches	21.095
Thunder Bay	Sb	Branches	20.873
Thunder Bay	Sb	Foliage	21.194
Thunder Bay	Sb	Foliage	21.046
Thunder Bay	Sb	Foliage	21.449
Thunder Bay	Sb	Foliage	21.727
Thunder Bay	Ta	Lower bole	19.801

Thunder Bay	Ta	Lower bole	19.080
Thunder Bay	Ta	Lower bole	21.527
Thunder Bay	Ta	Lower bole	19.522
Thunder Bay	Ta	Lower bark	21.564
Thunder Bay	Ta	Lower bark	21.428
Thunder Bay	Ta	Lower bark	20.587
Thunder Bay	Ta	Lower bark	20.832
Thunder Bay	Ta	Upper bole	19.643
Thunder Bay	Ta	Upper bole	19.473
Thunder Bay	Ta	Upper bole	21.189
Thunder Bay	Ta	Upper bole	19.556
Thunder Bay	Ta	Upper bark	20.846
Thunder Bay	Ta	Upper bark	22.243
Thunder Bay	Ta	Upper bark	21.673
Thunder Bay	Ta	Upper bark	20.892
Thunder Bay	Ta	Branches	21.572
Thunder Bay	Ta	Branches	19.072
Thunder Bay	Ta	Branches	20.470
Thunder Bay	Ta	Branches	19.477
Thunder Bay	Ta	Foliage	21.378
Thunder Bay	Ta	Foliage	21.470
Thunder Bay	Ta	Foliage	21.495
Thunder Bay	Ta	Foliage	21.539
Atikokan	Ab	Lower bole	19.004
Atikokan	Ab	Lower bole	19.034
Atikokan	Ab	Lower bole	19.123
Atikokan	Ab	Lower bole	18.811
Atikokan	Ab	Lower bark	17.968
Atikokan	Ab	Lower bark	17.773
Atikokan	Ab	Lower bark	18.546
Atikokan	Ab	Lower bark	18.007
Atikokan	Ab	Upper bole	19.180
Atikokan	Ab	Upper bole	19.199
Atikokan	Ab	Upper bole	19.332
Atikokan	Ab	Upper bole	18.952
Atikokan	Ab	Upper bark	17.651
Atikokan	Ab	Upper bark	18.229
Atikokan	Ab	Upper bark	18.369
Atikokan	Ab	Upper bark	18.823
Atikokan	Ab	Branches	19.435
Atikokan	Ab	Branches	19.408
Atikokan	Ab	Branches	18.554
Atikokan	Ab	Branches	19.078
Atikokan	Ab	Foliage	19.265
Atikokan	Ab	Foliage	18.752
Atikokan	Ab	Foliage	18.944
Atikokan	Ab	Foliage	19.547
Atikokan	Bf	Lower bole	19.385
Atikokan	Bf	Lower bole	19.869
Atikokan	Bf	Lower bole	20.041

Atikokan	Bf	Lower bole	20.294
Atikokan	Bf	Lower bark	21.387
Atikokan	Bf	Lower bark	22.182
Atikokan	Bf	Lower bark	21.378
Atikokan	Bf	Lower bark	21.114
Atikokan	Bf	Upper bole	19.871
Atikokan	Bf	Upper bole	19.835
Atikokan	Bf	Upper bole	21.074
Atikokan	Bf	Upper bole	20.175
Atikokan	Bf	Upper bark	21.550
Atikokan	Bf	Upper bark	21.293
Atikokan	Bf	Upper bark	20.000
Atikokan	Bf	Upper bark	20.485
Atikokan	Bf	Branches	21.012
Atikokan	Bf	Branches	21.194
Atikokan	Bf	Branches	21.132
Atikokan	Bf	Branches	20.835
Atikokan	Bf	Foliage	22.910
Atikokan	Bf	Foliage	23.041
Atikokan	Bf	Foliage	23.012
Atikokan	Bf	Foliage	23.271
Atikokan	Bw	Lower bole	19.695
Atikokan	Bw	Lower bole	19.862
Atikokan	Bw	Lower bole	19.341
Atikokan	Bw	Lower bole	19.788
Atikokan	Bw	Lower bark	27.474
Atikokan	Bw	Lower bark	26.497
Atikokan	Bw	Lower bark	26.205
Atikokan	Bw	Lower bark	27.011
Atikokan	Bw	Upper bole	20.538
Atikokan	Bw	Upper bole	20.576
Atikokan	Bw	Upper bole	19.793
Atikokan	Bw	Upper bole	19.581
Atikokan	Bw	Upper bark	25.419
Atikokan	Bw	Upper bark	24.300
Atikokan	Bw	Upper bark	23.824
Atikokan	Bw	Upper bark	23.922
Atikokan	Bw	Branches	22.260
Atikokan	Bw	Branches	21.441
Atikokan	Bw	Branches	20.029
Atikokan	Bw	Branches	21.379
Atikokan	Bw	Foliage	22.220
Atikokan	Bw	Foliage	20.430
Atikokan	Bw	Foliage	20.459
Atikokan	Bw	Foliage	20.789
Atikokan	Pj	Lower bole	19.806
Atikokan	Pj	Lower bole	20.298
Atikokan	Pj	Lower bole	20.448
Atikokan	Pj	Lower bole	20.451
Atikokan	Pj	Lower bark	21.618

Atikokan	Pj	Lower bark	21.823
Atikokan	Pj	Lower bark	21.969
Atikokan	Pj	Lower bark	21.700
Atikokan	Pj	Upper bole	19.328
Atikokan	Pj	Upper bole	19.121
Atikokan	Pj	Upper bole	21.022
Atikokan	Pj	Upper bole	20.642
Atikokan	Pj	Upper bark	20.246
Atikokan	Pj	Upper bark	20.617
Atikokan	Pj	Upper bark	20.371
Atikokan	Pj	Upper bark	19.974
Atikokan	Pj	Branches	20.094
Atikokan	Pj	Branches	20.527
Atikokan	Pj	Branches	21.137
Atikokan	Pj	Branches	20.522
Atikokan	Pj	Foliage	22.004
Atikokan	Pj	Foliage	21.978
Atikokan	Pj	Foliage	22.574
Atikokan	Pj	Foliage	22.205
Atikokan	Po	Lower bole	19.382
Atikokan	Po	Lower bole	19.041
Atikokan	Po	Lower bole	20.274
Atikokan	Po	Lower bole	19.054
Atikokan	Po	Lower bark	22.582
Atikokan	Po	Lower bark	22.355
Atikokan	Po	Lower bark	23.024
Atikokan	Po	Lower bark	22.561
Atikokan	Po	Upper bole	20.389
Atikokan	Po	Upper bole	19.634
Atikokan	Po	Upper bole	19.912
Atikokan	Po	Upper bole	19.660
Atikokan	Po	Upper bark	22.919
Atikokan	Po	Upper bark	22.067
Atikokan	Po	Upper bark	22.292
Atikokan	Po	Upper bark	22.786
Atikokan	Po	Branches	21.146
Atikokan	Po	Branches	21.962
Atikokan	Po	Branches	21.025
Atikokan	Po	Branches	20.661
Atikokan	Po	Foliage	21.525
Atikokan	Po	Foliage	21.205
Atikokan	Po	Foliage	21.501
Atikokan	Po	Foliage	21.360
Atikokan	Sb	Lower bole	19.977
Atikokan	Sb	Lower bole	19.466
Atikokan	Sb	Lower bole	19.587
Atikokan	Sb	Lower bole	19.209
Atikokan	Sb	Lower bark	19.461
Atikokan	Sb	Lower bark	19.326
Atikokan	Sb	Lower bark	20.670

Atikokan	Sb	Lower bark	20.047
Atikokan	Sb	Upper bole	19.921
Atikokan	Sb	Upper bole	19.475
Atikokan	Sb	Upper bole	19.324
Atikokan	Sb	Upper bole	19.330
Atikokan	Sb	Upper bark	18.785
Atikokan	Sb	Upper bark	19.746
Atikokan	Sb	Upper bark	20.305
Atikokan	Sb	Upper bark	19.509
Atikokan	Sb	Branches	21.066
Atikokan	Sb	Branches	20.213
Atikokan	Sb	Branches	20.698
Atikokan	Sb	Branches	20.235
Atikokan	Sb	Foliage	20.322
Atikokan	Sb	Foliage	20.642
Atikokan	Sb	Foliage	20.821
Atikokan	Sb	Foliage	21.175
Atikokan	Ta	Lower bole	19.105
Atikokan	Ta	Lower bole	19.635
Atikokan	Ta	Lower bole	19.218
Atikokan	Ta	Lower bole	19.818
Atikokan	Ta	Lower bark	20.523
Atikokan	Ta	Lower bark	21.547
Atikokan	Ta	Lower bark	21.652
Atikokan	Ta	Lower bark	20.033
Atikokan	Ta	Upper bole	19.185
Atikokan	Ta	Upper bole	20.735
Atikokan	Ta	Upper bole	19.393
Atikokan	Ta	Upper bole	19.545
Atikokan	Ta	Upper bark	21.028
Atikokan	Ta	Upper bark	21.223
Atikokan	Ta	Upper bark	20.256
Atikokan	Ta	Upper bark	20.427
Atikokan	Ta	Branches	20.592
Atikokan	Ta	Branches	20.724
Atikokan	Ta	Branches	19.706
Atikokan	Ta	Branches	19.451
Atikokan	Ta	Foliage	21.091
Atikokan	Ta	Foliage	21.534
Atikokan	Ta	Foliage	21.009
Atikokan	Ta	Foliage	20.875

APPENDIX 2
SPECIFIC GRAVITY RAW DATA

Site	Species	Component	Specific Gravity
Thunder Bay	Ab	Lower bole	0.661
Thunder Bay	Ab	Lower bole	0.602
Thunder Bay	Ab	Lower bole	0.599
Thunder Bay	Ab	Lower bole	0.607
Thunder Bay	Ab	Lower bark	0.521
Thunder Bay	Ab	Lower bark	0.617
Thunder Bay	Ab	Lower bark	0.556
Thunder Bay	Ab	Lower bark	0.565
Thunder Bay	Ab	Upper bole	0.626
Thunder Bay	Ab	Upper bole	0.601
Thunder Bay	Ab	Upper bole	0.616
Thunder Bay	Ab	Upper bole	0.619
Thunder Bay	Ab	Upper bark	0.572
Thunder Bay	Ab	Upper bark	0.504
Thunder Bay	Ab	Upper bark	0.627
Thunder Bay	Ab	Upper bark	0.799
Thunder Bay	Ab	Branches	0.600
Thunder Bay	Ab	Branches	0.747
Thunder Bay	Ab	Branches	0.725
Thunder Bay	Ab	Branches	0.680
Thunder Bay	Bf	Lower bole	0.401
Thunder Bay	Bf	Lower bole	0.324
Thunder Bay	Bf	Lower bole	0.393
Thunder Bay	Bf	Lower bole	0.376
Thunder Bay	Bf	Lower bark	0.693
Thunder Bay	Bf	Lower bark	0.708
Thunder Bay	Bf	Lower bark	0.665
Thunder Bay	Bf	Lower bark	0.719
Thunder Bay	Bf	Upper bole	0.399
Thunder Bay	Bf	Upper bole	0.424
Thunder Bay	Bf	Upper bole	0.388
Thunder Bay	Bf	Upper bole	0.373
Thunder Bay	Bf	Upper bark	0.665
Thunder Bay	Bf	Upper bark	0.743
Thunder Bay	Bf	Upper bark	0.687
Thunder Bay	Bf	Upper bark	0.687
Thunder Bay	Bf	Branches	0.644
Thunder Bay	Bf	Branches	0.575
Thunder Bay	Bf	Branches	0.506
Thunder Bay	Bf	Branches	0.526
Thunder Bay	Bw	Lower bole	0.571
Thunder Bay	Bw	Lower bole	0.583
Thunder Bay	Bw	Lower bole	0.570
Thunder Bay	Bw	Lower bole	0.580

Thunder Bay	Bw	Lower bark	0.674
Thunder Bay	Bw	Lower bark	0.583
Thunder Bay	Bw	Lower bark	0.623
Thunder Bay	Bw	Lower bark	0.560
Thunder Bay	Bw	Upper bole	0.592
Thunder Bay	Bw	Upper bole	0.592
Thunder Bay	Bw	Upper bole	0.586
Thunder Bay	Bw	Upper bole	0.632
Thunder Bay	Bw	Upper bark	0.647
Thunder Bay	Bw	Upper bark	0.616
Thunder Bay	Bw	Upper bark	0.571
Thunder Bay	Bw	Upper bark	0.541
Thunder Bay	Bw	Branches	0.653
Thunder Bay	Bw	Branches	0.616
Thunder Bay	Bw	Branches	0.671
Thunder Bay	Bw	Branches	0.674
Thunder Bay	Pj	Lower bole	0.489
Thunder Bay	Pj	Lower bole	0.473
Thunder Bay	Pj	Lower bole	0.476
Thunder Bay	Pj	Lower bole	0.466
Thunder Bay	Pj	Lower bark	0.607
Thunder Bay	Pj	Lower bark	0.638
Thunder Bay	Pj	Lower bark	0.617
Thunder Bay	Pj	Lower bark	0.624
Thunder Bay	Pj	Upper bole	0.473
Thunder Bay	Pj	Upper bole	0.460
Thunder Bay	Pj	Upper bole	0.469
Thunder Bay	Pj	Upper bole	0.455
Thunder Bay	Pj	Upper bark	0.780
Thunder Bay	Pj	Upper bark	0.693
Thunder Bay	Pj	Upper bark	0.695
Thunder Bay	Pj	Upper bark	0.712
Thunder Bay	Pj	Branches	0.526
Thunder Bay	Pj	Branches	0.546
Thunder Bay	Pj	Branches	0.523
Thunder Bay	Pj	Branches	0.550
Thunder Bay	Po	Lower bole	0.434
Thunder Bay	Po	Lower bole	0.422
Thunder Bay	Po	Lower bole	0.433
Thunder Bay	Po	Lower bole	0.419
Thunder Bay	Po	Lower bark	0.732
Thunder Bay	Po	Lower bark	0.729
Thunder Bay	Po	Lower bark	0.770
Thunder Bay	Po	Lower bark	0.736
Thunder Bay	Po	Upper bole	0.477
Thunder Bay	Po	Upper bole	0.454
Thunder Bay	Po	Upper bole	0.473
Thunder Bay	Po	Upper bole	0.435
Thunder Bay	Po	Upper bark	0.821
Thunder Bay	Po	Upper bark	0.861

Thunder Bay	Po	Upper bark	0.798
Thunder Bay	Po	Upper bark	0.803
Thunder Bay	Po	Branches	0.539
Thunder Bay	Po	Branches	0.538
Thunder Bay	Po	Branches	0.550
Thunder Bay	Po	Branches	0.485
Thunder Bay	Sb	Lower bole	0.552
Thunder Bay	Sb	Lower bole	0.561
Thunder Bay	Sb	Lower bole	0.534
Thunder Bay	Sb	Lower bole	0.418
Thunder Bay	Sb	Lower bark	0.659
Thunder Bay	Sb	Lower bark	0.717
Thunder Bay	Sb	Lower bark	0.698
Thunder Bay	Sb	Lower bark	0.846
Thunder Bay	Sb	Upper bole	0.586
Thunder Bay	Sb	Upper bole	0.574
Thunder Bay	Sb	Upper bole	0.610
Thunder Bay	Sb	Upper bole	0.543
Thunder Bay	Sb	Upper bark	0.678
Thunder Bay	Sb	Upper bark	0.741
Thunder Bay	Sb	Upper bark	0.690
Thunder Bay	Sb	Upper bark	0.677
Thunder Bay	Sb	Branches	0.692
Thunder Bay	Sb	Branches	0.669
Thunder Bay	Sb	Branches	0.659
Thunder Bay	Sb	Branches	0.635
Thunder Bay	Ta	Lower bole	0.611
Thunder Bay	Ta	Lower bole	0.584
Thunder Bay	Ta	Lower bole	0.544
Thunder Bay	Ta	Lower bole	0.646
Thunder Bay	Ta	Lower bark	0.717
Thunder Bay	Ta	Lower bark	0.622
Thunder Bay	Ta	Lower bark	0.645
Thunder Bay	Ta	Lower bark	0.673
Thunder Bay	Ta	Upper bole	0.552
Thunder Bay	Ta	Upper bole	0.668
Thunder Bay	Ta	Upper bole	0.522
Thunder Bay	Ta	Upper bole	0.554
Thunder Bay	Ta	Upper bark	0.639
Thunder Bay	Ta	Upper bark	0.600
Thunder Bay	Ta	Upper bark	0.613
Thunder Bay	Ta	Upper bark	0.623
Thunder Bay	Ta	Branches	0.630
Thunder Bay	Ta	Branches	0.560
Thunder Bay	Ta	Branches	0.564
Thunder Bay	Ta	Branches	0.582
Atikokan	Ab	Lower bole	0.634
Atikokan	Ab	Lower bole	0.654
Atikokan	Ab	Lower bole	0.630
Atikokan	Ab	Lower bole	0.688

Atikokan	Ab	Lower bark	0.559
Atikokan	Ab	Lower bark	0.619
Atikokan	Ab	Lower bark	0.558
Atikokan	Ab	Lower bark	0.537
Atikokan	Ab	Upper bole	0.649
Atikokan	Ab	Upper bole	0.667
Atikokan	Ab	Upper bole	0.565
Atikokan	Ab	Upper bole	0.700
Atikokan	Ab	Upper bark	0.685
Atikokan	Ab	Upper bark	0.847
Atikokan	Ab	Upper bark	0.683
Atikokan	Ab	Upper bark	0.469
Atikokan	Ab	Branches	0.638
Atikokan	Ab	Branches	0.672
Atikokan	Ab	Branches	0.758
Atikokan	Ab	Branches	0.739
Atikokan	Bf	Lower bole	0.434
Atikokan	Bf	Lower bole	0.354
Atikokan	Bf	Lower bole	0.376
Atikokan	Bf	Lower bole	0.421
Atikokan	Bf	Lower bark	0.689
Atikokan	Bf	Lower bark	0.689
Atikokan	Bf	Lower bark	0.744
Atikokan	Bf	Lower bark	0.698
Atikokan	Bf	Upper bole	0.448
Atikokan	Bf	Upper bole	0.382
Atikokan	Bf	Upper bole	0.439
Atikokan	Bf	Upper bole	0.500
Atikokan	Bf	Upper bark	0.718
Atikokan	Bf	Upper bark	0.733
Atikokan	Bf	Upper bark	0.707
Atikokan	Bf	Upper bark	0.682
Atikokan	Bf	Branches	0.647
Atikokan	Bf	Branches	0.682
Atikokan	Bf	Branches	0.555
Atikokan	Bf	Branches	0.649
Atikokan	Bw	Lower bole	0.705
Atikokan	Bw	Lower bole	0.641
Atikokan	Bw	Lower bole	0.657
Atikokan	Bw	Lower bole	0.698
Atikokan	Bw	Lower bark	0.673
Atikokan	Bw	Lower bark	0.712
Atikokan	Bw	Lower bark	0.626
Atikokan	Bw	Lower bark	0.694
Atikokan	Bw	Upper bole	0.705
Atikokan	Bw	Upper bole	0.610
Atikokan	Bw	Upper bole	0.627
Atikokan	Bw	Upper bole	0.667
Atikokan	Bw	Upper bark	0.668
Atikokan	Bw	Upper bark	0.634

Atikokan	Bw	Upper bark	0.615
Atikokan	Bw	Upper bark	0.537
Atikokan	Bw	Branches	0.654
Atikokan	Bw	Branches	0.622
Atikokan	Bw	Branches	0.655
Atikokan	Bw	Branches	0.676
Atikokan	Pj	Lower bole	0.487
Atikokan	Pj	Lower bole	0.401
Atikokan	Pj	Lower bole	0.471
Atikokan	Pj	Lower bole	0.526
Atikokan	Pj	Lower bark	0.680
Atikokan	Pj	Lower bark	0.562
Atikokan	Pj	Lower bark	0.654
Atikokan	Pj	Lower bark	0.663
Atikokan	Pj	Upper bole	0.484
Atikokan	Pj	Upper bole	0.481
Atikokan	Pj	Upper bole	0.419
Atikokan	Pj	Upper bole	0.486
Atikokan	Pj	Upper bark	0.718
Atikokan	Pj	Upper bark	0.763
Atikokan	Pj	Upper bark	0.695
Atikokan	Pj	Upper bark	0.710
Atikokan	Pj	Branches	0.616
Atikokan	Pj	Branches	0.562
Atikokan	Pj	Branches	0.540
Atikokan	Pj	Branches	0.554
Atikokan	Po	Lower bole	0.488
Atikokan	Po	Lower bole	0.497
Atikokan	Po	Lower bole	0.511
Atikokan	Po	Lower bole	0.556
Atikokan	Po	Lower bark	0.671
Atikokan	Po	Lower bark	0.700
Atikokan	Po	Lower bark	0.678
Atikokan	Po	Lower bark	0.709
Atikokan	Po	Upper bole	0.474
Atikokan	Po	Upper bole	0.486
Atikokan	Po	Upper bole	0.535
Atikokan	Po	Upper bole	0.510
Atikokan	Po	Upper bark	0.869
Atikokan	Po	Upper bark	0.915
Atikokan	Po	Upper bark	0.849
Atikokan	Po	Upper bark	0.894
Atikokan	Po	Branches	0.552
Atikokan	Po	Branches	0.589
Atikokan	Po	Branches	0.546
Atikokan	Po	Branches	0.565
Atikokan	Sb	Lower bole	0.442
Atikokan	Sb	Lower bole	0.496
Atikokan	Sb	Lower bole	0.489
Atikokan	Sb	Lower bole	0.551

Atikokan	Sb	Lower bark	0.703
Atikokan	Sb	Lower bark	0.702
Atikokan	Sb	Lower bark	0.696
Atikokan	Sb	Lower bark	0.640
Atikokan	Sb	Upper bole	0.418
Atikokan	Sb	Upper bole	0.476
Atikokan	Sb	Upper bole	0.515
Atikokan	Sb	Upper bole	0.543
Atikokan	Sb	Upper bark	0.798
Atikokan	Sb	Upper bark	0.728
Atikokan	Sb	Upper bark	0.702
Atikokan	Sb	Upper bark	0.730
Atikokan	Sb	Branches	0.717
Atikokan	Sb	Branches	0.656
Atikokan	Sb	Branches	0.648
Atikokan	Sb	Branches	0.710
Atikokan	Ta	Lower bole	0.521
Atikokan	Ta	Lower bole	0.647
Atikokan	Ta	Lower bole	0.678
Atikokan	Ta	Lower bole	0.622
Atikokan	Ta	Lower bark	0.671
Atikokan	Ta	Lower bark	0.622
Atikokan	Ta	Lower bark	0.658
Atikokan	Ta	Lower bark	0.747
Atikokan	Ta	Upper bole	0.564
Atikokan	Ta	Upper bole	0.562
Atikokan	Ta	Upper bole	0.555
Atikokan	Ta	Upper bole	0.510
Atikokan	Ta	Upper bark	0.665
Atikokan	Ta	Upper bark	0.641
Atikokan	Ta	Upper bark	0.701
Atikokan	Ta	Upper bark	0.697
Atikokan	Ta	Branches	0.564
Atikokan	Ta	Branches	0.601
Atikokan	Ta	Branches	0.538
Atikokan	Ta	Branches	0.548

APPENDIX 3
ASH CONTENT RAW DATA

Site	Species	Component	Ash Content %
Thunder Bay	Ab	Lower bole	0.519
Thunder Bay	Ab	Lower bole	0.714
Thunder Bay	Ab	Lower bole	0.711
Thunder Bay	Ab	Lower bole	0.647
Thunder Bay	Ab	Lower bark	8.597
Thunder Bay	Ab	Lower bark	9.430
Thunder Bay	Ab	Lower bark	8.074
Thunder Bay	Ab	Lower bark	10.651
Thunder Bay	Ab	Upper bole	0.825
Thunder Bay	Ab	Upper bole	1.225
Thunder Bay	Ab	Upper bole	1.269
Thunder Bay	Ab	Upper bole	0.879
Thunder Bay	Ab	Upper bark	7.458
Thunder Bay	Ab	Upper bark	7.077
Thunder Bay	Ab	Upper bark	7.588
Thunder Bay	Ab	Upper bark	8.210
Thunder Bay	Ab	Branches	3.451
Thunder Bay	Ab	Branches	3.766
Thunder Bay	Ab	Branches	3.401
Thunder Bay	Ab	Branches	2.104
Thunder Bay	Ab	Foliage	4.721
Thunder Bay	Ab	Foliage	8.015
Thunder Bay	Ab	Foliage	9.620
Thunder Bay	Ab	Foliage	9.932
Thunder Bay	Bf	Lower bole	0.561
Thunder Bay	Bf	Lower bole	0.874
Thunder Bay	Bf	Lower bole	0.936
Thunder Bay	Bf	Lower bole	1.028
Thunder Bay	Bf	Lower bark	2.433
Thunder Bay	Bf	Lower bark	2.806
Thunder Bay	Bf	Lower bark	3.088
Thunder Bay	Bf	Lower bark	2.334
Thunder Bay	Bf	Upper bole	0.286
Thunder Bay	Bf	Upper bole	0.765
Thunder Bay	Bf	Upper bole	0.877
Thunder Bay	Bf	Upper bole	0.773
Thunder Bay	Bf	Upper bark	2.131
Thunder Bay	Bf	Upper bark	2.799
Thunder Bay	Bf	Upper bark	2.588
Thunder Bay	Bf	Upper bark	2.727
Thunder Bay	Bf	Branches	1.846
Thunder Bay	Bf	Branches	1.685
Thunder Bay	Bf	Branches	2.334
Thunder Bay	Bf	Branches	1.842
Thunder Bay	Bf	Foliage	4.107

Thunder Bay	Bf	Foliage	4.554
Thunder Bay	Bf	Foliage	3.929
Thunder Bay	Bf	Foliage	4.499
Thunder Bay	Bw	Lower bole	0.293
Thunder Bay	Bw	Lower bole	0.213
Thunder Bay	Bw	Lower bole	0.196
Thunder Bay	Bw	Lower bole	0.214
Thunder Bay	Bw	Lower bark	2.247
Thunder Bay	Bw	Lower bark	2.360
Thunder Bay	Bw	Lower bark	2.142
Thunder Bay	Bw	Lower bark	2.519
Thunder Bay	Bw	Upper bole	0.214
Thunder Bay	Bw	Upper bole	0.231
Thunder Bay	Bw	Upper bole	0.106
Thunder Bay	Bw	Upper bole	0.207
Thunder Bay	Bw	Upper bark	2.532
Thunder Bay	Bw	Upper bark	1.949
Thunder Bay	Bw	Upper bark	1.527
Thunder Bay	Bw	Upper bark	1.461
Thunder Bay	Bw	Branches	1.419
Thunder Bay	Bw	Branches	0.823
Thunder Bay	Bw	Branches	0.664
Thunder Bay	Bw	Branches	0.638
Thunder Bay	Bw	Foliage	2.837
Thunder Bay	Bw	Foliage	2.849
Thunder Bay	Bw	Foliage	2.823
Thunder Bay	Bw	Foliage	3.077
Thunder Bay	Pj	Lower bole	0.000
Thunder Bay	Pj	Lower bole	0.091
Thunder Bay	Pj	Lower bole	0.356
Thunder Bay	Pj	Lower bole	0.083
Thunder Bay	Pj	Lower bark	1.278
Thunder Bay	Pj	Lower bark	1.418
Thunder Bay	Pj	Lower bark	1.529
Thunder Bay	Pj	Lower bark	1.585
Thunder Bay	Pj	Upper bole	0.194
Thunder Bay	Pj	Upper bole	0.364
Thunder Bay	Pj	Upper bole	1.855
Thunder Bay	Pj	Upper bole	0.263
Thunder Bay	Pj	Upper bark	0.549
Thunder Bay	Pj	Upper bark	1.235
Thunder Bay	Pj	Upper bark	1.534
Thunder Bay	Pj	Upper bark	1.366
Thunder Bay	Pj	Branches	0.481
Thunder Bay	Pj	Branches	0.512
Thunder Bay	Pj	Branches	0.623
Thunder Bay	Pj	Branches	0.736
Thunder Bay	Pj	Foliage	2.122
Thunder Bay	Pj	Foliage	1.997
Thunder Bay	Pj	Foliage	1.738

Thunder Bay	Pj	Foliage	2.002
Thunder Bay	Po	Lower bole	0.590
Thunder Bay	Po	Lower bole	0.649
Thunder Bay	Po	Lower bole	0.551
Thunder Bay	Po	Lower bole	0.624
Thunder Bay	Po	Lower bark	3.728
Thunder Bay	Po	Lower bark	3.297
Thunder Bay	Po	Lower bark	3.156
Thunder Bay	Po	Lower bark	3.957
Thunder Bay	Po	Upper bole	0.331
Thunder Bay	Po	Upper bole	0.562
Thunder Bay	Po	Upper bole	0.602
Thunder Bay	Po	Upper bole	0.438
Thunder Bay	Po	Upper bark	3.414
Thunder Bay	Po	Upper bark	3.102
Thunder Bay	Po	Upper bark	3.134
Thunder Bay	Po	Upper bark	3.095
Thunder Bay	Po	Branches	1.413
Thunder Bay	Po	Branches	2.020
Thunder Bay	Po	Branches	1.993
Thunder Bay	Po	Branches	1.684
Thunder Bay	Po	Foliage	4.967
Thunder Bay	Po	Foliage	4.783
Thunder Bay	Po	Foliage	4.738
Thunder Bay	Po	Foliage	3.924
Thunder Bay	Sb	Lower bole	0.333
Thunder Bay	Sb	Lower bole	0.314
Thunder Bay	Sb	Lower bole	0.408
Thunder Bay	Sb	Lower bole	0.513
Thunder Bay	Sb	Lower bark	2.617
Thunder Bay	Sb	Lower bark	10.741
Thunder Bay	Sb	Lower bark	2.390
Thunder Bay	Sb	Lower bark	2.589
Thunder Bay	Sb	Upper bole	0.598
Thunder Bay	Sb	Upper bole	-0.105
Thunder Bay	Sb	Upper bole	0.331
Thunder Bay	Sb	Upper bole	0.445
Thunder Bay	Sb	Upper bark	2.345
Thunder Bay	Sb	Upper bark	2.024
Thunder Bay	Sb	Upper bark	2.799
Thunder Bay	Sb	Upper bark	2.388
Thunder Bay	Sb	Branches	1.233
Thunder Bay	Sb	Branches	1.969
Thunder Bay	Sb	Branches	1.603
Thunder Bay	Sb	Branches	1.844
Thunder Bay	Sb	Foliage	2.100
Thunder Bay	Sb	Foliage	2.108
Thunder Bay	Sb	Foliage	2.002
Thunder Bay	Sb	Foliage	2.680
Thunder Bay	Ta	Lower bole	0.566

Thunder Bay	Ta	Lower bole	0.204
Thunder Bay	Ta	Lower bole	0.308
Thunder Bay	Ta	Lower bole	0.307
Thunder Bay	Ta	Lower bark	2.498
Thunder Bay	Ta	Lower bark	3.173
Thunder Bay	Ta	Lower bark	2.236
Thunder Bay	Ta	Lower bark	2.668
Thunder Bay	Ta	Upper bole	0.401
Thunder Bay	Ta	Upper bole	0.340
Thunder Bay	Ta	Upper bole	0.404
Thunder Bay	Ta	Upper bole	0.559
Thunder Bay	Ta	Upper bark	2.257
Thunder Bay	Ta	Upper bark	2.331
Thunder Bay	Ta	Upper bark	2.398
Thunder Bay	Ta	Upper bark	2.280
Thunder Bay	Ta	Branches	1.367
Thunder Bay	Ta	Branches	0.870
Thunder Bay	Ta	Branches	1.533
Thunder Bay	Ta	Branches	1.066
Thunder Bay	Ta	Foliage	3.036
Thunder Bay	Ta	Foliage	3.017
Thunder Bay	Ta	Foliage	2.995
Thunder Bay	Ta	Foliage	3.150
Atikokan	Ab	Lower bole	0.325
Atikokan	Ab	Lower bole	0.557
Atikokan	Ab	Lower bole	0.531
Atikokan	Ab	Lower bole	1.168
Atikokan	Ab	Lower bark	8.830
Atikokan	Ab	Lower bark	7.972
Atikokan	Ab	Lower bark	6.963
Atikokan	Ab	Lower bark	9.083
Atikokan	Ab	Upper bole	1.567
Atikokan	Ab	Upper bole	0.687
Atikokan	Ab	Upper bole	1.418
Atikokan	Ab	Upper bole	1.069
Atikokan	Ab	Upper bark	8.982
Atikokan	Ab	Upper bark	6.173
Atikokan	Ab	Upper bark	7.268
Atikokan	Ab	Upper bark	8.103
Atikokan	Ab	Branches	3.528
Atikokan	Ab	Branches	2.424
Atikokan	Ab	Branches	4.454
Atikokan	Ab	Branches	3.715
Atikokan	Ab	Foliage	9.731
Atikokan	Ab	Foliage	8.763
Atikokan	Ab	Foliage	8.717
Atikokan	Ab	Foliage	7.984
Atikokan	Bf	Lower bole	0.509
Atikokan	Bf	Lower bole	1.360
Atikokan	Bf	Lower bole	0.532

Atikokan	Bf	Lower bole	0.855
Atikokan	Bf	Lower bark	3.279
Atikokan	Bf	Lower bark	2.584
Atikokan	Bf	Lower bark	3.299
Atikokan	Bf	Lower bark	2.789
Atikokan	Bf	Upper bole	1.024
Atikokan	Bf	Upper bole	1.227
Atikokan	Bf	Upper bole	1.257
Atikokan	Bf	Upper bole	1.009
Atikokan	Bf	Upper bark	2.364
Atikokan	Bf	Upper bark	2.952
Atikokan	Bf	Upper bark	7.794
Atikokan	Bf	Upper bark	5.482
Atikokan	Bf	Branches	1.618
Atikokan	Bf	Branches	2.041
Atikokan	Bf	Branches	2.047
Atikokan	Bf	Branches	1.859
Atikokan	Bf	Foliage	3.895
Atikokan	Bf	Foliage	3.815
Atikokan	Bf	Foliage	4.024
Atikokan	Bf	Foliage	3.461
Atikokan	Bw	Lower bole	0.093
Atikokan	Bw	Lower bole	0.540
Atikokan	Bw	Lower bole	0.284
Atikokan	Bw	Lower bole	0.312
Atikokan	Bw	Lower bark	2.216
Atikokan	Bw	Lower bark	1.996
Atikokan	Bw	Lower bark	1.787
Atikokan	Bw	Lower bark	1.850
Atikokan	Bw	Upper bole	0.189
Atikokan	Bw	Upper bole	0.938
Atikokan	Bw	Upper bole	0.282
Atikokan	Bw	Upper bole	0.261
Atikokan	Bw	Upper bark	2.906
Atikokan	Bw	Upper bark	3.108
Atikokan	Bw	Upper bark	2.091
Atikokan	Bw	Upper bark	3.297
Atikokan	Bw	Branches	1.145
Atikokan	Bw	Branches	1.911
Atikokan	Bw	Branches	1.205
Atikokan	Bw	Branches	2.310
Atikokan	Bw	Foliage	5.444
Atikokan	Bw	Foliage	6.228
Atikokan	Bw	Foliage	6.407
Atikokan	Bw	Foliage	6.660
Atikokan	Pj	Lower bole	0.447
Atikokan	Pj	Lower bole	0.185
Atikokan	Pj	Lower bole	0.000
Atikokan	Pj	Lower bole	0.177
Atikokan	Pj	Lower bark	1.631

Atikokan	Pj	Lower bark	1.468
Atikokan	Pj	Lower bark	1.844
Atikokan	Pj	Lower bark	1.619
Atikokan	Pj	Upper bole	1.754
Atikokan	Pj	Upper bole	0.180
Atikokan	Pj	Upper bole	0.273
Atikokan	Pj	Upper bole	0.431
Atikokan	Pj	Upper bark	1.930
Atikokan	Pj	Upper bark	1.876
Atikokan	Pj	Upper bark	1.736
Atikokan	Pj	Upper bark	1.651
Atikokan	Pj	Branches	0.765
Atikokan	Pj	Branches	0.670
Atikokan	Pj	Branches	0.695
Atikokan	Pj	Branches	0.822
Atikokan	Pj	Foliage	1.936
Atikokan	Pj	Foliage	2.941
Atikokan	Pj	Foliage	2.035
Atikokan	Pj	Foliage	2.043
Atikokan	Po	Lower bole	0.282
Atikokan	Po	Lower bole	0.265
Atikokan	Po	Lower bole	0.361
Atikokan	Po	Lower bole	0.630
Atikokan	Po	Lower bark	3.966
Atikokan	Po	Lower bark	3.916
Atikokan	Po	Lower bark	3.197
Atikokan	Po	Lower bark	3.289
Atikokan	Po	Upper bole	0.378
Atikokan	Po	Upper bole	0.466
Atikokan	Po	Upper bole	0.366
Atikokan	Po	Upper bole	0.644
Atikokan	Po	Upper bark	2.505
Atikokan	Po	Upper bark	2.520
Atikokan	Po	Upper bark	2.683
Atikokan	Po	Upper bark	3.087
Atikokan	Po	Branches	3.194
Atikokan	Po	Branches	2.408
Atikokan	Po	Branches	2.352
Atikokan	Po	Branches	1.907
Atikokan	Po	Foliage	4.433
Atikokan	Po	Foliage	3.346
Atikokan	Po	Foliage	4.660
Atikokan	Po	Foliage	3.755
Atikokan	Sb	Lower bole	0.393
Atikokan	Sb	Lower bole	1.268
Atikokan	Sb	Lower bole	0.183
Atikokan	Sb	Lower bole	0.473
Atikokan	Sb	Lower bark	5.169
Atikokan	Sb	Lower bark	3.717
Atikokan	Sb	Lower bark	2.484

Atikokan	Sb	Lower bark	3.324
Atikokan	Sb	Upper bole	0.380
Atikokan	Sb	Upper bole	0.195
Atikokan	Sb	Upper bole	0.380
Atikokan	Sb	Upper bole	0.370
Atikokan	Sb	Upper bark	3.480
Atikokan	Sb	Upper bark	2.717
Atikokan	Sb	Upper bark	2.419
Atikokan	Sb	Upper bark	2.473
Atikokan	Sb	Branches	2.048
Atikokan	Sb	Branches	1.254
Atikokan	Sb	Branches	0.686
Atikokan	Sb	Branches	1.472
Atikokan	Sb	Foliage	4.714
Atikokan	Sb	Foliage	2.742
Atikokan	Sb	Foliage	2.908
Atikokan	Sb	Foliage	2.170
Atikokan	Ta	Lower bole	0.101
Atikokan	Ta	Lower bole	0.191
Atikokan	Ta	Lower bole	0.296
Atikokan	Ta	Lower bole	0.088
Atikokan	Ta	Lower bark	4.655
Atikokan	Ta	Lower bark	2.746
Atikokan	Ta	Lower bark	3.774
Atikokan	Ta	Lower bark	3.155
Atikokan	Ta	Upper bole	0.420
Atikokan	Ta	Upper bole	0.461
Atikokan	Ta	Upper bole	2.220
Atikokan	Ta	Upper bole	0.303
Atikokan	Ta	Upper bark	2.665
Atikokan	Ta	Upper bark	2.122
Atikokan	Ta	Upper bark	4.626
Atikokan	Ta	Upper bark	2.330
Atikokan	Ta	Branches	2.947
Atikokan	Ta	Branches	1.230
Atikokan	Ta	Branches	0.969
Atikokan	Ta	Branches	0.870
Atikokan	Ta	Foliage	1.141
Atikokan	Ta	Foliage	3.410
Atikokan	Ta	Foliage	3.019
Atikokan	Ta	Foliage	3.448

APPENDIX 4
MOISTURE CONTENTS OF FIRE BURNT WOOD RAW DATA

Species	Fire Name	Months	Moisture Content (%)
Po	Pace	12	49.21
Po	Pace	12	82.80
Po	Pace	12	51.00
Po	Pace	12	57.30
Po	Pace	12	31.70
Po	Pace	12	64.40
Po	Pace	12	39.40
Po	NLL	18	29.03
Po	NLL	18	18.70
Po	NLL	18	25.30
Po	NLL	18	63.80
Po	NLL	18	29.40
Po	NLL	18	32.60
Po	NLL	18	40.70
Po	Kitchen	24	32.09
Po	Kitchen	24	53.60
Po	Kitchen	24	22.50
Po	Kitchen	24	56.00
Po	Kitchen	24	69.00
Po	Kitchen	24	61.00
Po	Kitchen	24	50.00
Po	Armistice	37	44.45
Po	Armistice	37	28.50
Po	Armistice	37	20.50
Po	Armistice	37	18.60
Po	Armistice	37	20.20
Po	Armistice	37	19.50
Po	Armistice	37	32.20
Po	Quetico	52	46.97
Po	Quetico	52	51.30
Po	Quetico	52	45.20
Po	Quetico	52	20.70
Po	Quetico	52	43.50
Po	Quetico	52	22.70
Po	Quetico	52	47.50
Bf	Pace	12	32.72
Bf	Pace	12	20.60
Bf	Pace	12	22.90
Bf	Pace	12	19.40
Bf	Pace	12	31.80
Bf	Pace	12	26.80
Bf	Pace	12	33.00
Bf	NLL	18	19.05
Bf	NLL	18	19.80
Bf	NLL	18	15.10

Bf	NLL	18	20.70
Bf	NLL	18	21.20
Bf	NLL	18	39.40
Bf	NLL	18	24.70
Bf	Kitchen	24	18.11
Bf	Kitchen	24	14.80
Bf	Kitchen	24	17.80
Bf	Kitchen	24	17.80
Bf	Kitchen	24	18.20
Bf	Kitchen	24	17.40
Bf	Kitchen	24	19.60
Bf	Armistice	37	15.55
Bf	Armistice	37	16.50
Bf	Armistice	37	22.40
Bf	Armistice	37	23.40
Bf	Armistice	37	21.20
Bf	Armistice	37	16.00
Bf	Armistice	37	15.90
Bf	Quetico	52	24.16
Bf	Quetico	52	28.70
Bf	Quetico	52	21.80
Bf	Quetico	52	19.50
Bf	Quetico	52	24.50
Bf	Quetico	52	20.10
Bf	Quetico	52	19.20
Sb	Pace	12	21.50
Sb	Pace	12	20.10
Sb	Pace	12	26.10
Sb	Pace	12	26.50
Sb	Pace	12	17.00
Sb	Pace	12	24.30
Sb	Pace	12	22.00
Sb	NLL	18	17.85
Sb	NLL	18	17.20
Sb	NLL	18	20.10
Sb	NLL	18	21.90
Sb	NLL	18	28.20
Sb	NLL	18	18.80
Sb	NLL	18	28.70
Sb	Kitchen	24	15.59
Sb	Kitchen	24	16.50
Sb	Kitchen	24	16.30
Sb	Kitchen	24	16.40
Sb	Kitchen	24	17.60
Sb	Kitchen	24	16.90
Sb	Kitchen	24	18.40
Sb	Armistice	37	15.21
Sb	Armistice	37	21.40
Sb	Armistice	37	18.50
Sb	Armistice	37	19.20

Sb	Armistice	37	16.50
Sb	Armistice	37	14.20
Sb	Armistice	37	15.70
Sb	Quetico	52	21.73
Sb	Quetico	52	20.50
Sb	Quetico	52	20.70
Sb	Quetico	52	18.20
Sb	Quetico	52	36.00
Sb	Quetico	52	23.10
Sb	Quetico	52	20.40
Bw	Pace	12	49.94
Bw	Pace	12	38.10
Bw	Pace	12	50.20
Bw	Pace	12	63.20
Bw	Pace	12	36.80
Bw	Pace	12	38.70
Bw	Pace	12	42.00
Bw	NLL	18	50.11
Bw	NLL	18	35.50
Bw	NLL	18	39.50
Bw	NLL	18	31.70
Bw	NLL	18	50.70
Bw	NLL	18	43.60
Bw	NLL	18	54.60
Bw	Kitchen	24	47.26
Bw	Kitchen	24	39.00
Bw	Kitchen	24	46.00
Bw	Kitchen	24	56.50
Bw	Kitchen	24	26.50
Bw	Kitchen	24	23.90
Bw	Kitchen	24	47.00
Bw	Armistice	37	44.02
Bw	Armistice	37	65.20
Bw	Armistice	37	20.00
Bw	Armistice	37	27.00
Bw	Armistice	37	52.40
Bw	Armistice	37	27.00
Bw	Armistice	37	37.30
Bw	Quetico	52	41.43
Bw	Quetico	52	21.50
Bw	Quetico	52	25.10
Bw	Quetico	52	31.60
Bw	Quetico	52	48.70
Bw	Quetico	52	42.50
Bw	Quetico	52	52.50