COMPARISON OF *PICEA MARIANA*, *ABIES BALSAMEA*, *BETUAL PAPYRIFERA*, *POPULUS TREMULOIDES* FOR THE PRODUCTION OF WOOD PELLETS

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A Caution to The Reader

This HBEM thesis has been through a semi-final process of review and comment by at least two faculty members. It is made available for loan by the Faculty of Natural Resources Management to advance the practice of professional and scientific forestry. The reader should be aware that opinions and conclusions expressed in this document are those of the student and do not necessarily reflect the opinions of the thesis supervisor, the faculty, or of Lakehead University.

MAJOR ADVISOR COMMENTS

ABSTRACT

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Scientists and international organisations agree that wood pellets are a type of biofuel that is better for the environment than fossil fuels. Wood pellets are produced from the residues in sawmills, ground logs and is a renewable energy. Therefore, in this research we focus on the comparison of four tree species, *Picea mariana (Mill.) BSP., Abies balsamea (L.) Mill., Betula papyrifera Marsh.*, *Populus tremuloides Michx.* with their carbon content, thermal properties, and density to identify which species can produce the best wood pellets according to the results that we obtain from the studies. In this study we use ASTM standards to test the various properties of the wood and to compare and analyze. It was found that *Abies balsamea,* displayed the best properties to produce wood pellets due its significant properties compared to the other three species.

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INTRODUCTION

As the population of earth increases its natural resources are being depleted, due to the higher population. Hence the rate of deletion of non-renewable resources are comparatively higher than that of the past generations. The modern world has changed its viewpoint to renewable energy sources for fulfilling the future energy needs of the world. There are many vital renewable energies that are been extensively produced and scientifically studied. Wood pellets stand among the top renewable sources as the most effective and futuristic solutions for mankind. Canada is the second largest producer of wood pellets in the world, and most pellets it exports are sold in Europe and Asia (Forest products and applications, 2022).

Particles of wood are compressed for use as fuel and wood pellets (Jones et al., 2012). In the beginning, wood pellets were only designed for small-scale and for local domestic uses, and bark and sawdust, which are two products of the forest industry, were primarily used as a raw material for pellet production (Kuokkanen et al., 2009). A wood pellet is made mechanically from a uniform substance that has initially been hammered and ground into a homogeneous dough-like mass and then squeezing it through a heated press to form a cylindrical shape (Kuokkanen et al., 2009). Fossil fuels create high CO_2 gas emission which are produced in the process of generating electricity with the help of non-renewable fossil fuel sources. To aid in reducing CO_2 emissions, biomass co-firing might play an important role because it is an efficient way to convert biomass into electricity with the help of a boiler system with less greenhouse gases emissions (Tsuchiya & Yoshida, 2017). The creation of renewable fuel sources to produce energy, such as wood pellets, has become very popular in recent years (Alakangas and Virkkunen 2007). Wood pellets have many advantages, including high density and heat value and low moisture content, and are relatively convenient to transport and store (Obernberger and Thek 2010).

Understanding the vital role of wood pellets in the future this study aims to compare four Boreal tree species to determine the most effective and efficient tree species in the production of wood pellets.

OBJECTIVE

The main objective of this thesis is to test and find out the wood properties of four different trees, the tests shall be run in various labs and will follow international testing standards. From the tests we will be able to calculate their carbon content, thermal properties, and density to identify which species can produce the best wood pellets based on properties.

HYPOTHESIS

From the results of the wood samples of four different trees, wood samples of the tree with the higher carbon and calorific value and lower emission of gases will be identified as the best producer of high-graded wood pellet.

2.0 LITRATURE REVIEW

2.1 PRODUCTION AND APPLICATION OF WOOD PELLETS

2.1.1. Wood Pellet Production

At present wood pellet production has evolved and is divided into various stages such as, accumulating, drying, hammer-milling, pelletizing, cooling, screening, and packing (Nunes et al., 2013). Wood pellets have a cylindrical form, are glossy, and look from white to brown. The initial phase in the manufacture of wood pellets is the production of raw materials. Typically, the by-product of another wood production activity serves as the raw material, there are several wood leftovers produced by the wood industry that may be utilised to make wood pellets, including sawdust, bark, planer shavings, woodchips, whole ground trees unused by log industries etc. (Jones et al., 2012).

2.1.2. Steps Involved in Wood Pellet Production

Wood pellet production is divided into 4 main steps as: -

1) Chipping and Crushing
2) Drying
3) Pelletizing
4) Cooling

2.1.2.1. Chipping and Crushing

The size and kind of the biomass determine the number of grinding processes. There are two main stages for grinding. The first stage, known as "the coarse grinding stage," involves running the material through a "chipper" to turn the raw wood into chips resembling those produced by a pulp woodchipper. After that, raw materials must be screened to remove any impurities, such as metal, plastic, and stones (Kofman, 2010). The next stage involves grinding the material to a particle size no more than 3 mm using a hammer mill grinder (Ciolkosz, 2010).

2.1.2.2. Drying

According to the Ciolkosz (2010), the moisture content of the woody raw material is required to be approximately 15%. The optimal moisture percentage for raw materials, according to Liu and Lu (2000), is around 8%. The required moisture content of the ground raw material before the pelletization process was stated by each of the authors previously mentioned in a variety of ranges, therefore it is producer dependent. However, before pelletization, the raw material must be dried if it doesn't fit the stipulated manufacturer's standard. In contrast, if it is too wet, the trapped steam pressure weakens internal connections and lowers the mechanical qualities, causing breakage and dust during future handling. If it is too dry, the heat build-up caused by friction in the pelletizer burns the surfaces (Spelter and Toth, 2009). There are a few types of dryers: drum-type, belt-drier, tube bundle drier, and the low-temperature drier (Obernberger and Thek, 2010). Dryers can employ direct drying, indirect drying, or a combination of the two. Whereas indirect or contact drying uses heat provided by a heat exchanger via the metal walls, direct drying relies on the application of hot air to the raw material (Mujumdar, 2011).

2.1.2.3. Pelletizing

To make it easier to transport, handle, and use, raw wood is compressed during the pelletization process into a homogenous product with a greater energy density and lower moisture content (Spelter and Toth, 2009). Typically, raw materials are preheated to

120°C to 130°C using dry steam before pressing. This process increases the lignin's plasticity and aids in tying raw material particles together (Kofman, 2010). Ring or flat die pellet mills are typically used by large-scale producers, with ring die mills being the most prevalent (Haslinger, 2005). Die rings and fixed rollers are the basic components of every ring die pellet mill. The material is fed into the rollers in a sideways fashion and forced through the die's boreholes from the inside out. The die produces an unlimited string that either randomly breaks up into fragments or is surgically cut into the required dimensions of 6 or 8 mm in diameter and 3.15 mm in length. Also, a bulk density of more than or equal to 600 Kg/m^3 (Obernberger and Thek, 2010).

2.1.2.4. Cooling

After the above steps, the temperature of the pellets might range from 80°C to 130°C (Louis, 2011). The most popular coolers for pellets are belt coolers and counter flow coolers. The pellets lose moisture and stiffen while cooling, resulting in a final moisture content that can be as low as 6% following the cooler (Kofman, 2007). Moreover, chilling increases the pellets mechanical durability, which should be more than or equal to 97.5^5 percentage of total pellet mass and fines standards of less than 3.15 mm (EPC 2013). Pellets may be carried in bulk or packaged in bags of varying capacities when cooling is complete (Louis, 2011).

2.1.3. Wood Pellet Application

As a result of its potential to reduce greenhouse gas emissions by partially replacing coal and other fossil fuel systems for power and heating, biofuels have been generally touted to be a viable fossil fuel substitute. Bioenergy systems may be integrated and optimised to greatly reduce greenhouse gas emissions and have fewer effects on the environment and society (Antizar & Turrion, 2010). In 2015, the world generated 28 million tonnes of wood pellets. With 14.1% annual growth, the market for selling wood pellets to power plants that use them to generate electricity and heat is stable. The production of electricity from biomass has several advantages such as low costs and high availability and less impact on the environment as well as ease to transport (Greinert et al., 2019). In Canada, wood pellets are gaining popularity in the production of electricity and power for both businesses and households (Dwivedi et al., 2014).

2.2 PROPERTIES OF RESEARCH SPECIES

In this research paper we compare the characteristic features of four species which are *Picea mariana (Mill.) BSP.* (Black Spruce), *Abies balsamea (L.) Mill.* (Balsam Fir), *Betula papyrifera Marsh.* (White Birch), *Populus tremuloids Michx.* (Poplar).

2.2.1. *Picea mariana* (Black Spruce)

Black spruce may grow in a variety of conditions, which means it can grow upland and lowland having various wood fibre properties Average black spruce trees are about 15 meters in height (Baldwin K.A. and Sims R.A., 1997), in locations where there are many fires, black spruce grows in broad, evenly aged stands. Otherwise, it typically creates asymmetrical stands by vegetative layering, particularly in open spaces with plenty of humus (Giroud et al. 2016). Black spruce wood is important for making engineered wood products, lumber, and pulp. In comparison to balsam fir, black spruce is denser (Table 1), has stronger elasticity and rupture moduli, as well as increased coarseness for the same fibre length. Black spruce wood is not a resilient material by nature, and when exposed to moisture and weathering, it is vulnerable to deterioration and insect assault. It is typically regarded as having little resistance to deterioration (Forest Products Laboratory, 1987).

It burns fiercely because its high density and low moisture content, making it an effective fuel source. Black Spruce wood pellets are a safe and clean fuel option since they burn with a low flame and little smoke, black spruce typically has an ash level of less than 0.5%, which is regarded as being extremely low (Rossi et al. 2015). Black spruce wood pellets burn more efficiently than pellets manufactured from other species due to their low ash content (Rossi et al. 2015). Black spruce is a desirable alternative for individuals seeking a cost-effective solution to heat their house because it is also a very affordable option for producing wood pellets. In terms of wood density and mechanical properties, black spruce and jack pine are similar, but black spruce has smaller knots and substantially less resin (Giroud et al. 2016).

Black spruce grows throughout a broad transcontinental stretch from Alaska to Newfoundland, but only in northern North America where it forms huge, closed forests. The forest industry in Quebec particularly appreciates this species for its richness and advantageous traits (Rossi et al. 2015).

Table 1 - wood density and calorific value of species. (Kryla, 1984[1]; Sinclair and Barnes, 1984[2]; Klašnja et al. 2013[3]; Gruber et al. 2021[4])

	Bf	Po	Bw	Sb
Calorific value (MJ/Kg)	20.6[2]	18.812[4]	20.66[3]	20.3[1]
Density (Kg/m3)	436.5[2]	375[4]	402[3]	450[1]

2.2.2. *Abies balsamea* (Balsam Fir)

The balsam fir is a small to medium-sized tree that grows to an average height of 15 meters and more (Baldwin K.A. and Sims R.A., 1997). It is a tolerant boreal forest plant that commonly thrives alongside white spruce and birch trees or in relatively unspoiled stands. Balsam fir frequently sprouts from seeds in dark, enclosed spaces. This kind of tree has a short lifetime; heart rot affects a large percentage of trees older than 90 years. Balsam fir is a prominent commercial timber species in North America, with pulp being its primary use. Nonetheless, it is a prominent species of wood and is frequently provided in the Spruce-Pine-Fir grade together with spruces (Sinclair 1984).

Balsam fir is the perfect wood for creating wood pellets since it has a high energy content (Table 1). The sapwood and heartwood of the light-colored wood are identical. It basically has no flavour or smell after being dried. The number of knots in the timber is often large, even though the knots themselves are frequently little. When it ages, it loses lustre and turns greyish. With a total area of around 150 million acres, it is one of the most frequently cultivated softwood tree species in North America.

2.2.3. *Populus tremuloides* (Poplar)

The wood of all poplar species is diffusely porous and has a low density (Table 1). Poplar has an average height of about 21 meters in height and can grow up to 34 meters tall (Baldwin K.A. and Sims R.A., 1997). Poplars have rather weak strength traits. But, when it comes to bending strength and stiffness, they fare well when compared to common construction species like spruce, pine, and fir. So, in North America's enormous building markets, poplar-based wood products, such as lumber, composite panels, and structural composite lumber products, may effectively compete with those made from softwood (Dickmann 2001).

Because it grows swiftly and is readily accessible, poplar is seen as an abundant and renewable resource. This lowers the energy used to produce the pellets, lowering the cost of manufacture (Lyubov et al. 2021) The low calorific value of poplar and its bark for dry and ash-free weight is comparable to the values found for spruce, however poplar and its bark performs poorly due to the greater ash content in terms of low calorific value for dry weight.

According to Dickmann (2001), for several reasons poplar is a suitable crop to grow in forests. The enormous poplar tree has a limited lifespan, prefers moisture and full sunshine, and grows swiftly (Dickmann 2001). Furthermore, because poplars can be cloned, heritable traits can emerge in them more quickly than in other tree species that cannot. Hybrid poplars are specifically produced to improve disease resistance, volume output, and length of wood fibres for a particular site situation (Balatinecz, J.J. and Kretschmann, D.E., 2001). Once established, poplars don't require replanting since their coppicing root structure enables plants to do so on their own. Suckers that emerge from stumps or roots after trees have been harvested create the next crop.

2.2.4. *Betula papyrifera* (White Birch)

The common white birch is a significant part of mixed hardwood stands in the boreal forest (Safford et al. 1990). This is because white birch has significant genetic variety in growth, shape, and drought tolerance, allowing it to endure a wide range of climatic circumstances (Simard et al. 1997). White birch has a height of approximately 15 meters (Baldwin K.A. and Sims R.A., 1997). One of the more economically significant hardwood species in Canada's boreal forest is white birch, which is utilized in the value-added sector to produce high-quality veneer and furniture goods. Due to its high density, low moisture content, and high calorific value, white birch is a good wood species similar to balsam fir for making wood pellets (Table 1). Its low moisture content and high density make it an efficient fuel that is also simple to carry and store. Additionally, it is a cost-effective fuel option due to its high calorific value. White birch pellets are also renowned for having less ash, which makes them a sustainable fuel option. White birch pellets are a perfect fuel source for interior heating since they also provide a steady flame and little smoke (Lekounougou, 2011).

2.3 COMMON SPECIES USED FOR WOOD PELLET PRODUCTION

To produce wood pellets, several different tree species are employed. The most popular types of wood utilized are softwoods like pine and spruce. While more costly, hardwoods like oak and maple are also utilized. The kinds of trees that are utilized to produce wood pellets will vary depending on the cost and accessibility of the raw materials. Softwood pellets are often easy to ignite and are suitable for home use. Although hardwood pellets are more costly, they are more durable and create more heat. Pellets made of softwood and hardwood both have benefits and drawbacks. The type of tree species utilized affects the characteristics of wood pellets. The availability and price of the raw materials will determine the type of tree species that is employed.

2.4 INFLUENCIAL PROPERTIES OF A HIGH-GRADED WOOD PELLET

There are various vital properties of wood pellets that affect the efficiency of electricity generation. Many of the properties are co-dependent on the tree species from which the pellet is produced. In this study we are testing three wood pellet properties, namely wood density, ash content, calorific value, carbon content of four different tree species which are Balsam Fir, Black Spruce, White Birch, and trembling aspen which will help to identify tree species that can be used to produce premium wood pellets and table 2 shows the ideal wood pellet parameters.

Table 2 - Summary table of wood pellet parameter interdependencies and the EU and PFI standard values (Obernberger and Thek, 2010; Pellet Fuel Institute, 2010) (Tarasov,2013).

Wood Pellet Parameters	Unit	prEN-14961	PFI
Calorific Content	MJ/Kg	> 16.5	N/A
Ash Content	%	< 0.7	<1
Fines	%	N/A	<0.5

2.4.1. Wood Density

Wood density measures the amount of actual wood material in a unit volume of wood. The way we reach that measurement is to calculate the ratio between an mass of wood divided by the volume of the wood. A higher wood density is closely correlated with greater wood strength, which is why it is often regarded as a crucial measure of how valuable a wood is in terms of its mechanical capabilities (Hart 2010). Forest managers would find it valuable to know how to manage for greater density wood given the correlation between wood density and the value of the wood. Greater the wood density higher will be the calorific and carbon values of the wood samples.

2.4.2. Ash Content

The quantity of inorganic waste left behind after a fuel has burned under specific conditions is known as the ash content (or total ash), and it is often stated as a percentage of the mass of dry matter in the fuel. Calcium, magnesium, silicon, and potassium are the principal components of ash in wood (Obernberger and Thek, 2010). High ash content can have a negative impact on stove efficiency, it can also display a negative effect on the calorific value. The EU regulation states that the ash content of premium class pellets must be 0.7% or below (Thek and Obernberg, 2010).

2.4.3. Calorific Value

The amount of energy generated from full combustion per unit of mass or volume is known as the calorific value or heating value (Obernbereger and Thek, 2010). The calorific value of wood pellets is crucial since it determines customer value. The energy that can be produced from a given amount of product the higher the heating value (Tarasov, 2013). The average gross calorific value of softwoods in Canada is 21.18 MJ/kg, whereas that of hardwoods is 19.35 MJ/kg (Kryla, 1984). Softwood species' wood pellets range in gross calorific value from 19.66 to 20.36 MJ/kg, whereas hardwood species' pellets range from 17.63 to 20.81 MJ/kg (Telmo and Lousada, 2011). Hardwood pellets' range of net calorific value is 14.41 to 17.91 MJ/kg, whereas softwood pellets' range is 15.63 to 16.94 MJ/kg (Telmo and Lousada, 2011). Calorific value is determined by using a bomb calorimeter, it works on the idea of constant volume combustion, which involves burning a substance in a closed container and measuring the heat released as a change in the system's temperature. (Parr Instrument Co., 2007).

2.4.4 Carbon Content

The primary component of biomass fuels is carbon (C), along with hydrogen (H), and oxygen (O), because these components are present in cellulose, hemicellulose, and lignin (Dujmovic 2017). The carbon content of different species and even individual trees can differ, such as early and late woods which is average per growth ring (Lamlom and Savidge 2003). In general, softwood species have a greater carbon content than hardwood species, which is consistent with a 10% difference in lignin concentration between softwood and hardwood species. In comparison to early wood, late wood typically has greater cellulose levels and lower lignin levels which is average per growth ring. The different types of wood found inside trees as well as stocking density must be considered when estimating the carbon content of forest stands. The gross calorific value of woody biomass is larger due to the higher carbon content compared to herbaceous biomass (Obernberger and Thek, 2010).

3.0 MATERIALS AND METHODS

The focus of this study is to perform various wood property tests and analyse the different results with the four tree species that were collected from the forest. The four tree species that are being studied are *Picea mariana* (Black Spruce), *Abies balsamea* (Balsam Fir), *Betula papyrifera* (White Birch), *Populus tremuloides* (Trembling Aspen). Density test, Calorific value test and Carbon tests are the three test that were preformed using the tree samples in the Lakehead University Wood Science Testing Facility (LUWSTF) and the results of the experiment were acquired by comparing the three test results of the four species.

3.1 MATERIALS

Various instruments were used during the experiments. During the initial stages of the test sample preparation a few instruments used were a mini chainsaw, band saw, measuring scale, markers and storage containers (Figure 1).

Figure 1 - Basic materials used.

3.1.1 Wood Density Test

The Materials that were used for the Wood Density test were blocks of juvenile samples and mature samples of the four tree species, two measuring scales with one of them a 4-pt. scale and the other 2 pt. scale with a beaker filled with water, one picker (Figure 2).

Figure 2 - Wood density instruments

3.1.3 Calorific Value Test

The materials that were used for the Calorific Value tests were combined granulated wood samples of juvenile samples and mature samples of the four tree species, a Parr 6200 Bomb Calorimeter with water handling system (Figure 3).

Figure 3 - Bomb calorimeter

<u>3.1.4 Carbon Value Test</u>

The materials that were used for Carbon Value test were granulated wood samples of juvenile and mature wood of the four tree species, and a CHNS Analyzer (Elemetar Vario EL Cube)

3.2 METHODOLOGY

The tree samples that were collected from the forest were later cut using a mini chainsaw and the top juvenile portion and the bottom matured portion was differentiated. After that the four wood samples were labeled from the pith to the outer bark with 1” inch and this was done using a scale and marker for both the top and bottom samples (Figure 4).

Figure 4 - Wood samples labeled 1" from pith to bark.

The marked samples were taken to the LUWSTF and cut into small blocks of wood samples using a Band saw, the blocks were precisely cut using the markings on the samples. The block sample of the four species were separately kept in eight containers with the juvenile and matured stages samples in different containers. Finally, these samples were stationed inside the oven which was kept at 70 degrees Celsius for about a week to dry out the moisture content for further tests.

After one week the samples were taken out of the oven to do the wood density test which was done using the water displacement method (Density = Mass/Volume) in Kg/m^3 and later kept back for another week to dry. Finally, for the other test the wood samples had to be chipped into smaller pieces and ground into powder form and for this the wood blocks of the four species were chipped using a chisel and a hammer and the chip samples were kept in cylindrical plastic containers that were marked with the tree species, whether it was the juvenile or mature samples and the marking number that was done initially (Figure 5).

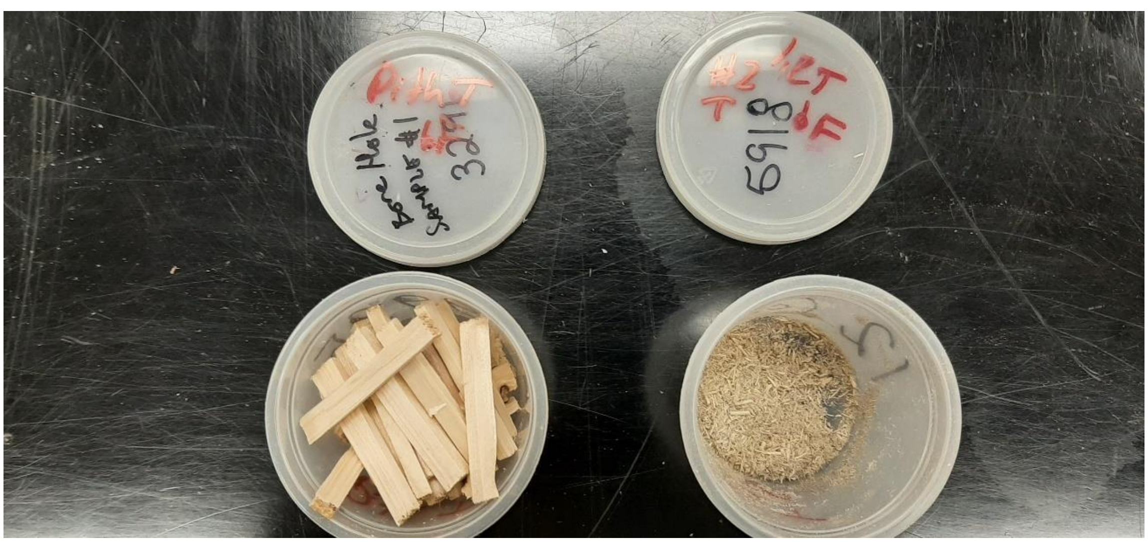

Figure 5 - chipped and ground wood samples

After this the chip samples were ground into powder using a Wiley-Mill grinder in the LUWSTF and the samples were then put into one container and marked as a whole. Later these powdered samples were used to run the remaining two test (Calorific and Carbon).

3.2.1 Wood Density

Each wood block sample piece was weighed on a 4-point balance to ascertain its mass value, and then it was submerged in water, where the volume indicator scale provided a volume value, to calculate the density of wood using the equation of mass divided by volume (water displacement method) (Figure 6). The densities of the juvenile and mature wood of four tree species were determined by substituting these two values into the density equation, all the procedures followed ASTM standards for calculating wood density (ASTM D2395-17).

Figure 6 - Water displacement method

3.2.3 Calorific Value

The amount of energy generated from full combustion per unit of mass or volume is known as the calorific value (Obernbereger and Thek, 2010). A bomb calorimeter is used to calculate calorific value (Parr Instrument Co., 2007). The calorific values were obtained by using (ASTM E870-82). This Standard describes how to use a bomb calorimeter calibrated by the burning of approved benzoic acid to determine the gross calorific value of a solid biofuel at constant volume and at 25 °C as a temperature (ISO 18125:2017). The sample holder was then put into the bomb, tightly closed, and inflated with oxygen to 450 psi. After that, a metal bucket containing 2 L of distilled water was placed with the bomb inside. Fuse wires were attached to the bomb once it had been filled with oxygen and placed inside the bucket, which was then placed inside the calorimeter chamber. Next the calorimeter's lid was secured. The sample's original weight was entered into the calorimeter software before the run was fired. Finally, once the run is fired and completed and the sample burnt, the bomb calorimeter calculated the gross heat of combustion (Tarasov, 2013).

3.2.4 Carbon content

The instrument and sample preparation involved a CHNS analyzer, activating the carrier gas and heating the furnaces to working temperatures (Kepka. G, 2016). The recommended sample sequence includes blanks, conditioning samples, standards for daily factor determination, quality check samples, and real samples (Kepka. G, 2016). To weigh the samples, shape the tin foil into a cup or use a boat, tare it to zero, add sample additive if needed, fill with sample, close it air-tight, and press it to form a tablet (Kepka. G, 2016). To start the procedure, insert the samples, enter weight, and sample name, set oxygen dosing time, start the analysis process, and evaluate the measurement after it is finished. The carbon percentage values were obtained by following (ASTM E872-82(2019) in the Lakehead University Centre for Analytical Services labs.

4.0 RESULT

4.1 WOOD DENSITY

The wood density of the four species were calculated and the data was analysed and made into graphs and shown below, where table 1 accounts for the wood density of mature wood and relates to the outer ring circles of the mature wood sample (1.3, 2.3, 3.3, 4.3) and the table 4 show the wood density of juvenile wood found in the inner ring sample (1.1 , 2.2 , 3.1 , 4.1). (Table 3 & 4, Figure 7 & 8): -

Table 3. Wood density of mature wood

MATURE WOOD	Bw	Bf	Sb	Po
1.3	531.1836	511.5442	472.81	382.1464
2.3	556.9773	416.3616	454.6974	393.004
3.3	570.1073	426.1088	455.9212	390.9672
4.3	544.3579	413.3535	457.4701	388.9915

Table 4. Wood density of juvenile wood

JUVENILE WOOD	Bw	Bf	Sb	Po
1.1	564.5889	374.9676	559.9044	424.5475
2.1	579.6739	387.8261	533.0846	421.5474
3.1	586.8901	400.2704	532.6661	439.9451
4.1	553.3494	377.7654	524.4864	434.6045

Hence from the above Table 3 and Table 4 we understand that common samples of each species were accounted to compare the wood density between the juvenile and mature stages of the species.

Figure 7- Wood density (mature stage)

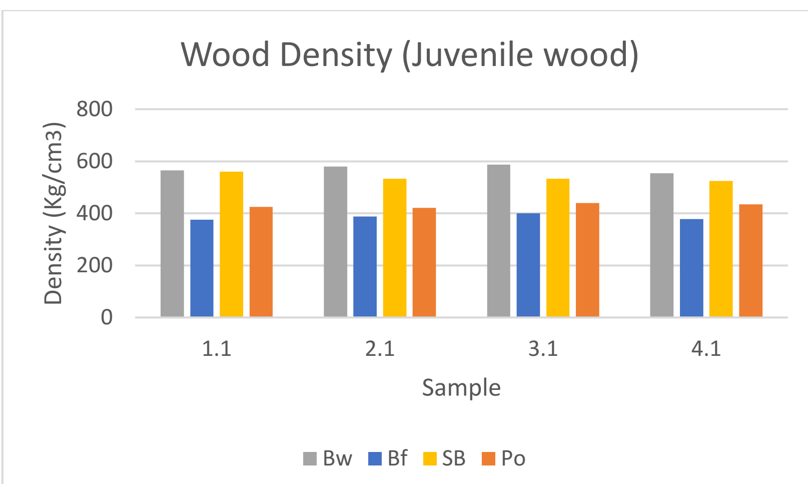

Figure 8. Wood density (juvenile stage)

Hence after analysing Figure 7 and Figure 8, White Birch has the highest wood density in both juvenile and mature stage and poplar has the lowest wood density in mature wood stage and balsam fir has the lowest in the juvenile stage.

4.2 CALORIFIC VALUE

The calorific values of four species were calculated and the data was depicted into tables and graphs as given below (Table 5 &6 , Figure 9 &10), table 5 shows the calorific values of mature samples, also inner and outer which represents the juvenile and mature samples of the bottom of the tree respectively and table 6 shows the calorific value of the juvenile samples, also inner and outer in this table represents the inner and outer sides of the juvenile stage sample :-

Table 5. Calorific values of mature samples

Mature Sample	Bf	Po	Bw	Sb
Outer	20.059	19.4132	20.1039	19.1423
Inner	20.1798	20.1521	17.5167	19.1261
Average	20.1194	19.78265	18.8103	19.1342

Table 6. Calorific values of juvenile samples

Juvenile Sample	Bf	Po	Bw	Sb
Outer	19.8371	19.3656	18.4477	19.1394
Inner	18.7762	19.8301	19.4494	
Average	19.30665	19.59785	18.94855	19.1394

Tables 5 and 6 depicts the accumulated values of the inner and outer samples of both mature and juvenile stages of the four species, the average of the calorific values were calculated to analyse the highest and the lowest calorific values among the species.

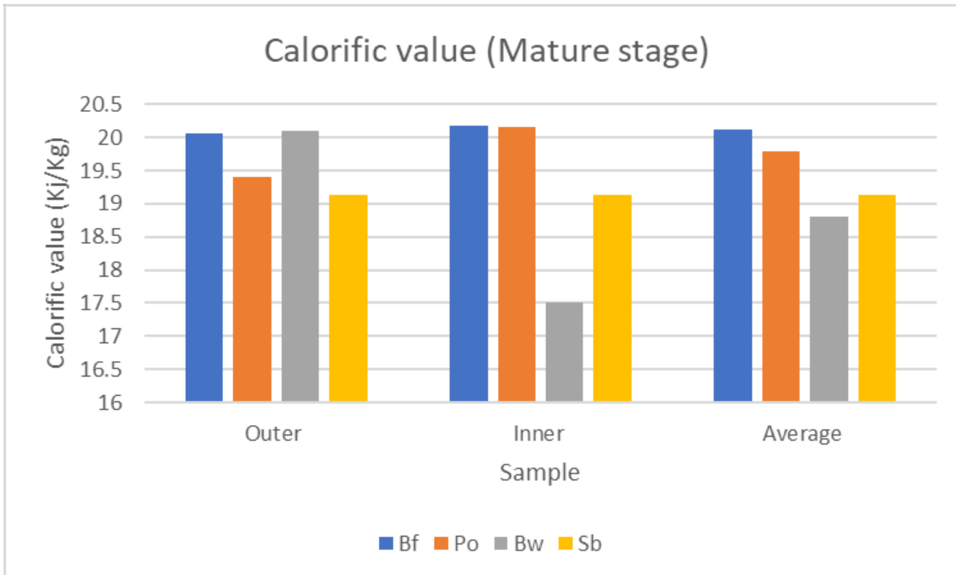

Figure 9. Calorific values (mature stage)

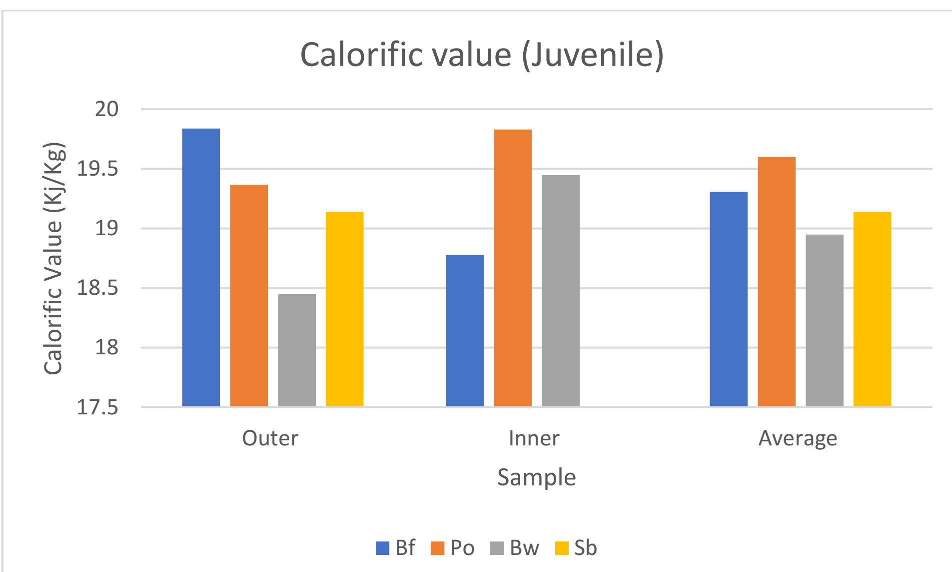

Figure 10. Calorific value (juvenile stage)

Observing the figures 9 and 10 and analyzing the averages of the calorific value we conclude that during juvenile stage Poplar has the highest calorific value and the least calorific value is White birch statistically. On the other hand, in the mature stage balsam fir has the highest value and white birch has the least calorific value statistically.

4.3 CARBON CONTENT

The carbon values of the four species were identified and illustrated into graphs and tables are shown below (Table 7, Figure 11): -

Table 7. Carbon content table

Sample	Bf	Po	Bw	Sb
Outer	49.02	47.56	47.99	48.61
Inner	49.07	48.29	47.91	48.51
Average	49.045	47.925	47.95	48.56

Table 7 identifies the carbon percentages in each of the samples of the four species which were divided into inner and outer samples and finally the averages were taken to identify the species with the greatest and least carbon percentage.

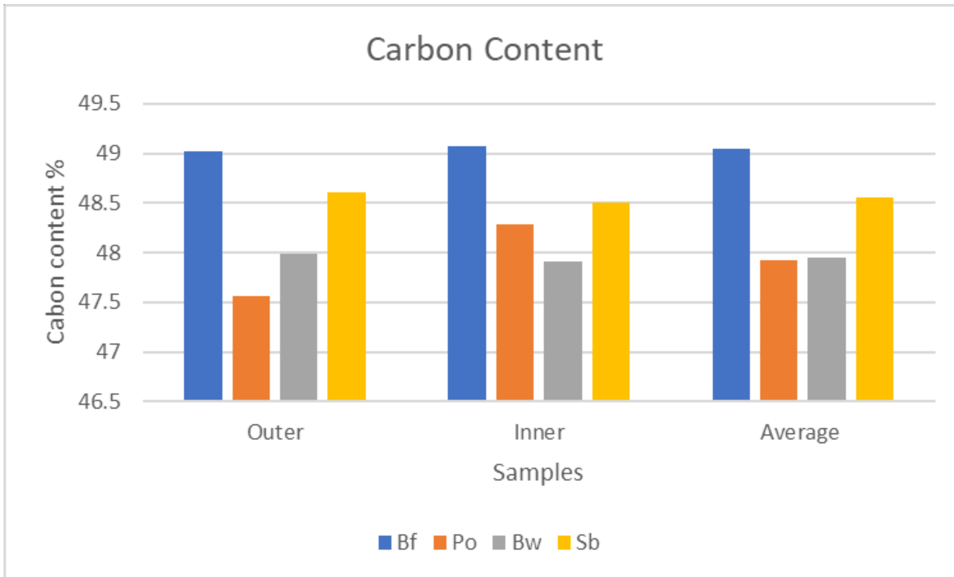

Figure 11. Carbon content % graph

From figure 11 the inner and outer samples of the species varies differently but the accumulated average values of the samples depict, Balsam fir has the highest carbon content present, and the least was found to be the poplar species (table 7).

Table 8 - Results table

Sample	Bf	Po	Bw	Sb	Ideal
Wood Density	2nd	4th	1st	3rd	High
Calorific value	1st	2nd	4th	3rd	high
Carbon Value	1st	4th	3rd	2nd	High
Results	1st	4th	3th	2nd	

Therefore, from table 8 we understand that by comparing the four samples using three different testing methods, all the four species would be good for pellet production and all the species showed standards pellet properties. Moreover, all the species meet the standards of pellet properties, Balsam fir comparatively had the highest calorific value and carbon value which would be the best species among the four species.

5.0 DISCUSSION

This study focused on finding the most suitable tree species that could be dedicated to the biomass producers to produce high value energy outputs in high-graded wood pellets. Various tests were used to conclude which species would provide the best properties for wood pellets, which is discussed below.

Table 9 - Pellet properties of four species (Kryla, 1984[1]; Sinclair and Barnes, 1984[2]; Klašnja et al. 2013[3]; Gruber et al. 2021[4])

	Bf	Po	Bw	Sb
Calorific value (MJ/Kg)	20.6[2]	18.812[4]	20.66[3]	20.3[1]
Density (Kg/m3)	436.5[2]	375[4]	402[3]	450[1]

5.1 WOOD DENSITY

Wood density as mentioned in the literature review is one of the key properties in identifying a good wood pellet species and it accounts for carbon present in the sample which also related to the calorific value of the species (Hart 2010), regarding log quality and the product's structural integrity, wood density is one of the most crucial wood properties. According to this study it was found out that White birch has the highest wood density among the four species as seen in Table 3 & 4, Figure 7 & 8, the lowest species with the density was found to be Poplar; but when we compare the results of similar studies according to Table 9 (Kryla, 1984; Sinclair S.A. and Barnes D.P., 1984; Klašnja et al. 2013; Gruber et al. 2021) we find that balsam fir has the highest wood density while poplar has comparatively lower density.

5.2 CALORIFIC VALUE

The calorific value of wood pellets is crucial since it determines customer value, which determines the burning ability of a species, hence this was taken as our next test to differentiate between the four species and from the results (Obernbereger and Thek, 2010). From (Table 5 &6, Figure 9 &10) we understand that highest calorific value was found to be in balsam fir and the lowest was found to be in white birch species. According to table 9, White birch was found to be the species with highest calorific values and the lowest was found to be poplar.

5.3 CARBON CONTENT

The final aspect of this study was to run carbon test on the species which eventually helped us in understanding the carbon value of each species. From the table 7 and figure 11 we had identified that balsam fir was the species with the highest carbon content and the species with the least carbon content was found out to be poplar. Particularly the balsam fir has been found to have good carbon sequestration properties, making it an eco-friendly option for biomass firms looking to reduce greenhouse gas emissions.

When the results were compared with other studies of similar interest such, they showed identical results data which was found to be in this study as well. According to Kryla (1984), black spruces species showed a calorific value of 20.3 MJ/Kg in the results, which was not identical to the 19.1 MJ/Kg found in this study. Also the Sinclair and Barnes (1984) studies more about the properties of balsam fir and its utilization the results in their study showed that calorific value of balsam fir was found to be 20.60 MJ/Kg and the value in this study was 19.3 MJ/Kg, which were also different according to this study. According to Klašnja et al. (2013), it was found that white birch had a calorific value of 20.66 MJ/Kg and a wood density of 402 Kg/m^{3,} where the values in this study were found to be not identical. The calorific values and wood density values of poplar was found to be 18.812 MJ/Kg and 375 Kg/m^3 Respectively which was found in the study done by Gruber et al. 2021(Table 9).

Hence by analyzing the whole data that we acquired in the results, we can come into a conclusion that all the test that we conducted had concluded that balsam fir was the best species to produce premium wood pellets for the biomass industries, wherein poplar would be the least favoured in the list of four, But when the similar studies are compared and analyzed we find that white birch has comparatively higher density and calorific values which makes it the better species for wood pellets out of the four species. Hence this contradicts our results and we come into a conclusion where the wood species can be variable according to different factors such as location, soil types and competition, also the samples that were taken for this research was limited in quality, which could have created a change in the results.

6.0 CONCLUSION

In conclusion, it can be concluded that of the four species, namely *Picea Mariana*, *Abies balsamea*, *Betula papyrifera*, and *Populus tremuloides*, Balsam Fir (*Abies balsamea*) stands out as the most suitable species for the production of high-grade wood pellets for biomass industries after analyzing and comparing the data that was found in this research. Balsam Fir has several advantageous qualities, including solid wood with a high energy content, a moderate rate of growth, and a low ash level upon combustion. It is a viable option for the production of wood pellets because it is also abundantly accessible in North America.

The results of this thesis emphasize how crucial it is to take species-specific traits into account when choosing trees for wood pellet production. Due to its positive characteristics, balsam fir emerges as a feasible option for biomass manufacturers looking for high-grade wood pellets. Further testing and examination of different parameters, along with additional research, analysis, and study would give a more complete knowledge and validate the conclusion. Making educated selections would also benefit from speaking with specialists in the biomass and wood pellet industries. Balsam Fir (*Abies balsamea)* emerges as a suitable species for biomass enterprises looking to create high-grade wood pellets while simultaneously boosting carbon sequestration, considering both the wood pellet production qualities and carbon sequestration potential. Biomass companies can support sustainable and environmentally friendly practices in the production of renewable biomass energy by selecting tree species with properties that are advantageous for both the production of wood pellets and carbon sequestration.

The findings of this thesis suggest that Poplar (*Populus tremuloides*) is the least preferred species among the four examined for the manufacture of high-grade wood pellets for biomass industries, and that Balsam Fir (*Abies balsamea*) is the best-suited species. These discoveries advance our knowledge of how wood pellets are made and give the biomass sector new information on which tree species to choose for high-quality wood pellet manufacturing. More studies can be run of these species which are grown in different locations as further studies for this topic to attain more knowledge of the species and their properties.

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APPENDICES

Table 10. Density of *Betula papyrifera* (White Birch), (mature wood stage)

	Sample	Dry Weight (g)	Dry Volume (cm3)	Density g/cm3	Kg/m3
Bw (bottom)	Pith	16.2011	30.5	0.531183607	531.1836
	1.1	14.1112	25.82	0.546522076	546.5221
	1.2	15.6851	27.27	0.575177851	575.1779
	1.3	3.9296	6.21	0.632785829	632.7858
	2.1	14.7042	26.4	0.556977273	556.9773
	2.2	9.8978	15.69	0.630834927	630.8349
	3.1	14.8741	26.09	0.570107321	570.1073
	3.2	16.7499	30.49	0.549357166	549.3572
	3.3	7.7014	12.9	0.597007752	597.0078
	4.1	12.5039	22.97	0.544357858	544.3579
	4.2	13.5291	24.12	0.56090796	560.908
	4.3	8.9053	13.79	0.64577955	645.7796

Table 11. Density of *Betula papyrifera* (White Birch), (juvenile wood stage)

	Sample	Dry Weight (g)	Dry Volume (cm3)	Density g/cm3	Kg/m3
Bw (top)	Pith	17.3613	30.54	0.568477407	568.4774
	1.1	14.2841	25.3	0.564588933	564.5889
	2.1	14.7527	25.45	0.57967387	579.6739
	3.1	14.0971	24.02	0.586890092	586.8901
	3.2	7.3504	12.38	0.593731826	593.7318
	4.1	11.4488	20.69	0.553349444	553.3494
	4.2	10.5276	18.09	0.581956882	581.9569

Table 12. Density of *Abies balsamea* (Balsam Fir), (mature wood stage)

	Sample	Dry Weight (g)	Dry Volume (cm3)	Density g/cm3	Kg/m3
Bf (Bottom)	Pith	21.7799	48.66	0.447593506	447.5935
	1.1	18.6509	36.46	0.511544158	511.5442
	1.2	14.2096	35.64	0.398698092	398.6981
	1.3	16.0825	35.25	0.456241135	456.2411
	1.4	14.3032	33.09	0.432251435	432.2514
	1.5	6.3337	17.31	0.365898325	365.8983
	2.1	18.1492	43.59	0.416361551	416.3616
	2.2	15.37	36.95	0.415967524	415.9675
	3.1	16.4478	38.6	0.426108808	426.1088
	3.2	6.023	15.29	0.393917593	393.9176
	4.1	15.0006	36.29	0.413353541	413.3535
	4.2	15.718	36.45	0.43122085	431.2209
	4.3	10.9626	30.39	0.360730503	360.7305

Table 13. Density of *Abies balsamea* (Balsam Fir), (juvenile wood stage)

	Sample	Dry Weight (g)	Dry Volume (cm3)	Density g/cm3	Kg/m3
Bf (top)	Pith	14.975	38.3	0.390992167	390.9922
	1.1	9.8429	26.25	0.374967619	374.9676
	1.2	4.5466	16.64	0.273233173	273.2332
	2.1	14.8072	38.18	0.387826087	387.8261
	2.2	9.2892	24.27	0.382744129	382.7441
	3.1	7.5491	18.86	0.400270414	400.2704
	3.2	8.0783	21.41	0.377314339	377.3143
	4.1	9.1457	24.21	0.377765386	377.7654

Table 14. Density of *Picea mariana* (Black Spruce), (mature wood stage)

	Sample		Dry Weight (g)	Dry Volume (cm3)	Density g/cm3	Kg/m3
SB (Bottom)	Pith		21.7048	46.65	0.465269025	465.269
		1.1	16.2032	34.27	0.472810038	472.81
		1.2	20.2103	38.3	0.527684073	527.6841
		1.3	14.545	27.38	0.531227173	531.2272
		2.1	15.4779	34.04	0.454697415	454.6974
		2.2	14.9572	29.97	0.499072406	499.0724
		2.3	19.1828	31.31	0.612673267	612.6733
		3.1	17.4709	38.32	0.45592119	455.9212
		3.2	19.2974	36.98	0.521833423	521.8334
		3.3	18.5663	31.13	0.596411821	596.4118
		4.1	15.3161	33.48	0.457470131	457.4701
		4.2	17.8401	37.09	0.480994877	480.9949
		4.3	22.6799	42.08	0.538971008	538.971

Table 15. Density of *Picea mariana* (Black Spruce), (juvenile wood stage)

	Sample		Dry Weight (g)	Dry Volume (cm3)	Density g/cm3	Kg/m3
SB (Top)	Pith		16.7275	29.3	0.570904437	570.9044
		1.1	12.594	22.49	0.559982214	559.9822
		2.1	12.3569	23.18	0.533084556	533.0846
		3.1	12.5869	23.63	0.532666102	532.6661
		4.1	13.7363	26.19	0.524486445	524.4864

Table 16. Density of *Populus tremuloides* (poplar), (mature wood stage)

	Sample	Dry Weight (g)	Dry Volume (cm3)	Density g/cm3	Kg/m3
Po (Bottom)	Pith	13.7918	37.1	0.371746631	371.7466
	1.1	12.4274	32.52	0.382146371	382.1464
	1.2	12.1232	30.8	0.39361039	393.6104
	2.1	12.8866	32.79	0.393003965	393.004
	2.2	10.9968	26.55	0.41419209	414.1921
	3.1	15.7247	40.22	0.390967181	390.9672
	3.2	15.753	38.86	0.405378281	405.3783
	3.3	10.6198	25.55	0.41564775	415.6477
	4.1	11.4558	29.45	0.388991511	388.9915
	4.2	12.3794	30.12	0.411002656	411.0027
	4.3	12.7395	31.95	0.398732394	398.7324

Table 17. Density of *Populus tremuloides* (poplar), (juvenile wood stage)

	Sample	Dry Weight (g)	Dry Volume (cm3)	Density g/cm3	Kg/m3
Po (Top)	Pith	17.0613	38.06	0.448273778	448.2738
	1.1	13.5091	31.82	0.424547454	424.5475
	2.1	14.1935	33.67	0.421547372	421.5474
	3.1	16.036	36.45	0.43994513	439.9451
	3.2	9.7792	22.24	0.43971223	439.7122
	4.1	10.1654	23.39	0.434604532	434.6045
	4.2	5.7676	14.08	0.409630682	409.6307

Table 18. Calorific values of mature samples

Mature	Sample	Weight of sample (g)	Results (Kj/Kg)
Bf	1.1+2.1+3.1+4.1	1.0202	20.059
	1.2+2.2+3.2+4.2	1.0254	20.1798
Po	1.1+2.1+.3.1+4.1	1.0149	19.4132
	1.2+2.2+3.2+4.2	1.0332	19.6468
	3.3+4.3	1.0127	20.1521
Bw	1.1+2.1+3.1+4.1	1.0287	20.1039
	1.2+2.2+3.2+4.2	1.0327	17.156
	1.3+3.3+4.3	1.0609	17.5167
Sb	1.1+2.1+3.1+4.1	1.0344	19.1423
	1.2+2.2+3.2+4.2	1.0676	19.9285
	1.3+2.3+3.3+4.3	1.0511	19.1261

Table 19. Calorific values for juvenile samples

Juvenile	Sample	Weight of sample (g)	Results (Kj/Kg)
Bf	1.1+2.1+3.1+4.1	1.0006	19.8371
	1.2+2.2+3.2	1.0223	18.7762
Po	1.1+2.1+3.1+4.1	1.0184	19.3656
	3.2+4.2	0.9955	19.8301
Bw	1.1+2.1+3.1+4.1	1.0407	18.4477
	3.2+4.2	1.0919	19.4494
Sb	1.1+2.1+3.1+4.1	1.0274	19.1394

Table 20. Carbon content table

Sample	C%
Balsam Fir 1.1	49.02
Balsam Fir 1.2	49.07
Poplar 1.1	47.56
Poplar 3.3	48.29
White Birch 1.1	47.99
White Birch 1.3	47.91
Black Spruce 1.1	48.61
Black Spruce 1.3	48.51