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Benefits of Supply Chain Management for the Canadian Forest Sector and Option in the Woody Biomass Supply Chain for Energy Production

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ABSTRACT

The entire supply chain is the decision focus in supply chain management (SCM) which stretches from the raw materials to ultimate consumption. To derive the maximum benefits from the use of SCM in the Canadian forest sector it is essential to apply it in a proper way. Material flows in the forest industry are divergent and interrelated. The costing model of the entire supply chain, from stump to product, can be applied to reduce the total product cost while maximizing its value. To better compete in the global market Canadian forest companies need to include the woody biomass for energy production in the supply chain. For short distances truck transport is the most economical mode of biomass transportation. For long distances trucks can be used to bring biomass from the field to the nearest train station, after which the train can transport biomass to the destination. The costs of the woody biomass supply chain can be reduced by integrating woody biomass harvesting with conventional forest harvesting.
KEYWORDS: Canadian Forest Sector, Cost, Energy, Learning Curve, Supply Chain Management, Woody biomass

1. INTRODUCTION

The term supply chain management (SCM) is an important tool used by many firms which helps them to compete in international markets (Haartveit *et al.* 2004; Poirier 1999). There are different synonyms of SCM, such as total production management, logistical management, holistic approach and total system costing (Ellram 1991; Cooper *et al.*1997; Christopher 1998; Meredith and Shafer 1999; Mentzer 2001; Pulkki 2001; Haartveit *et al.* 2004; Annevelink and de Mol 2007). SCM can be defined as the proper planning, organization, development, coordination, steering and control of intra and inter-organizational processes in a holistic approach including exchanges of information, materials, cash, product development activities and product marketing activities in supply chains (Mattsson 1999; Haartveit *et al.* 2004).

The entire supply chain is the decision focus in SCM which stretches from the raw materials to ultimate consumption. The companies can fulfill their overall objectives and they can also increase future opportunities by avoiding sub-optimization of lower level operations (Pulkki 2001). SCM develops better knowledge of the overall process chain by the cooperation within and between organizations. SCM helps achieve many important breakthroughs of the process, such as improving yield, improving productivity, reducing cost, improving product quality and introducing new products (Mattsson 1999; Pulkki 2001; Haartveit *et al.* 2004; Alam and Pulkki 2009; Alam *et al.* 2011).

The main goal of SCM is to improve overall profitability and competitiveness of the firms in the supply chain (Ellram 1991; Persson 1997; Chopra and Meindl 2001; Haartveit *et al.* 2004). Several SCM strategies have been proposed. Some SCM strategies can seem to be contradictory: e.g., reducing lead times while increasing customization; and increasing service while reducing inventories. Due to confusion and misinterpretation about SCM, often SCM initiatives fail to achieve targets (Fisher 1997; Fine 1998; Stank *et al.* 1999; Haartveit *et al.* 2004).

In general, SCM is customer oriented where market pull is a significant factor. Traditionally forest products industries sell their commodity products with push marketing. SCM initiatives in these types of supply chains were set up to improve efficiencies by increasing throughput and reducing inventories. A holistic approach can be applied by integrating processes across companies for the potential improvements of efficiencies of the supply chain (Haartveit *et al.* 2004).

The purpose of this paper is, by conducting a literature review, to determine the benefits of SCM for the Canadian forest sector by integrating economically feasible and sustainable alternatives of woody biomass supply chains for energy production. This literature review is aimed at synthesizing the knowledge on SCM of woody biomass for energy production which has been done by different researchers.

2. How scm will benefit Canadian forest sector

To derive the maximum benefits from the use of SCM for the Canadian forest sector it is essential to apply it in a proper way (Alam *et al.* 2009). It is necessary to know the nature of material flows in the forest industries. During describing their characteristics many important aspects must be considered, such as structure and association of actors, lead times, and the degree of push or pull along the supply chain (Haartveit *et al.* 2004).

Material flows in the forest industry are divergent and interrelated. In this supply chain products from one processing stage are the raw materials for other segments. Traditionally the forest industry supply chains are complex and long with many intermediaries between resource product extraction, product manufacturing and product end use (Sinclair 1992; Nerman 2000).

In the diverging material flows through forest industry supply chains the production of one forest product produces other concurrent forest products: e.g., the production of one type of lumber produces additional lumber products of other qualities and dimensions. The additional products produced during the production of a certain product are called consequence products (Nerman 2000;

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Markgren and Lycken 2001; Rask and Andersson 2001; Haartveit *et al.* 2004). Lumber manufacturing processes cannot completely be controlled due the uncertainty of raw material and the dependency between products (Nerman 2000; Markgren and Lycken 2001; Rask and Andersson 2001). The situation becomes more complex when a considerable percentage of total products produced constitute by-products: e.g., chips for pulp and paper, and woody biomass for energy production. In lumber manufacturing, both consequence products and by-products are important determinants of profitability (Haartveit *et al.* 2004).

Due to recent changes in the preference of customer satisfaction in forest industry supply chains (Mattsson 2000), the customization trends are observed in lumber remanufacturing (Haartveit *et al.* 2004). Inventory holding costs can be reduced by proper customization. Increasing customization sometimes creates some concerning issues in the supply chain, such as smaller batch sizes, more frequent machine set-ups, increased delivery lead times and reduced capacity utilization. To overcome these challenges appropriate complex planning and scheduling are necessary (McDougall 1999; Pulkki 2001; Alam and Pulkki 2009). The main objective of forest products companies in Canada has been overall profit maximization. However, in most cases decisions are made based on the optimal solution of sub-problems: e.g., minimum roadside cost, minimum mill-site cost, etc. By the solution of sub-problems Canadian forest industries cannot compete in the global market (Pulkki 2001; Haartveit *et al.* 2004; Alam and Pulkki 2009).

At present many forest industries are re-focusing on the customer rather than on raw material supply and the trend on reducing inventories of roundwood has been started (Högnäs 2000; Haartveit *et al.* 2004). Generally apportion between firms helps provide better returns by reducing cost and increasing efficiency (Carlsson and Rönnqvist 1999; Haartveit *et al.* 2004). However, planning a supply chain becomes complex due to closer integration: e.g., forest harvesting decision at the early stage of supply chain impacts manufacturing outcomes at the later stages of the chain. To make the forest industry supply chain successful, integration and customer orientation by joint planning, management and coordination based on trust and loyalty between different actors involved in the supply chain are essential (Pulkki 2001; Haartveit *et al.* 2004).

Many researchers introduced the concept of SCM in forest industries (Andersson *et al*. 1999; Carlsson and Rönnquist 1999; Kenny 1999; Lehtonen 1999; McDougall 1999; Palevich 1999; Peterson *et al.* 1999; Högnäs 2000; Helstad *et al.* 2001; Pulkki 2001; Smith 2001; Juslin and Hansen 2002; Haartveit *et al.* 2004). They discussed the potential benefits of SCM for forest industries. By applying SCM the potential for improving performance and profitability of forest industries has yet to be realized (Haartveit *et al.* 2004).

Canadian forest companies need to apply SCM strategies to compete internationally. Otherwise it will be difficult for them to survive today's market (Pulkki 2001). They have to produce high quality and price competitive products. Forest companies must always take care of customer needs. At present good customer service is one of the most important ways to maintain business success. If forest companies do not implement strategies to improve the quality of products and to apply better customer service it will be difficult for them to be profitable. At the same time they have to increase the knowledge content of their products to compete in the global market (Zhang and Gingras 1999; Pulkki 2001; Juslin and Hansen 2002; Haartveit *et al.* 2004; Alam and Pulkki 2009).

The focus of decision making in forestry is very complex. Figure 1 shows that decision-making focus in forestry must be the entire supply chain from tree improvement right through forest management planning, silviculture, roads, cutting and extraction, transport, mill processing, transport/storage to final customer. By applying this holistic approach the maximum value/benefit can be achieved from forest resources by increasing wood/fibre yield, by improving wood/fibre quality and by decreasing production costs (Pulkki 2001; Haartveit *et al.* 2004; Alam and Pulkki 2009; Alam 2011).

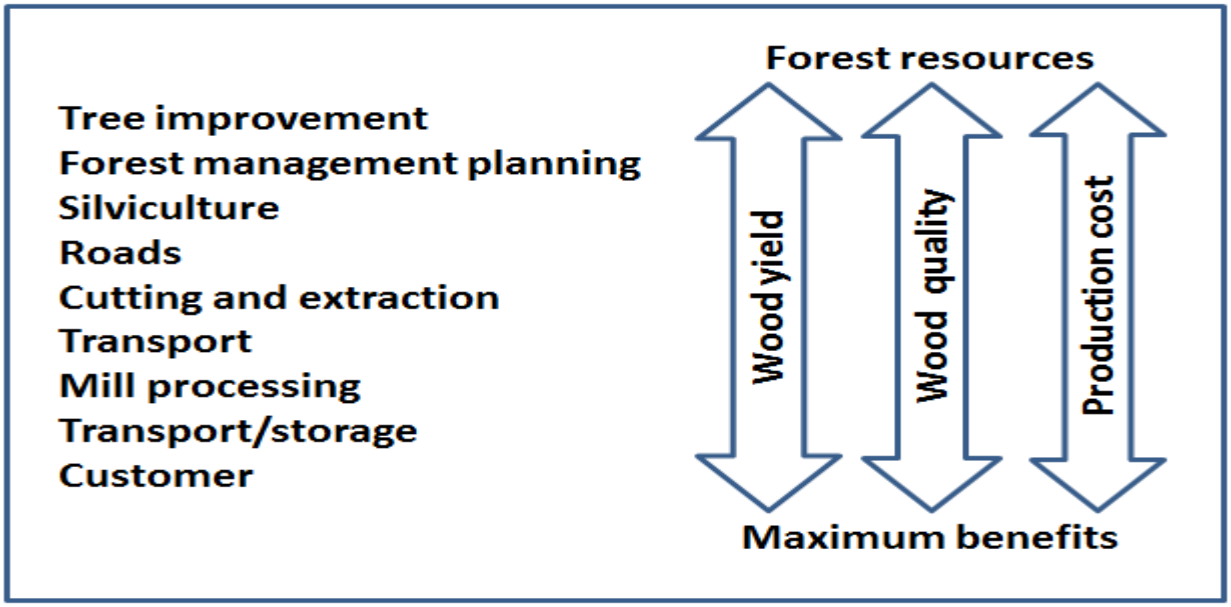

Figure 1: Decision-making focus in forestry supply chain (Pulkki 2001)

The costing model of the entire supply chain, from stump to product, can be applied to maximize value including overall profit. Pulkki (2001) showed how the cost of forestry supply chains can be reduced by analyzing the entire supply chain. He indicated that decisions on wood procurement need to be taken based on total cost and product quality. SCM can help ensure both environmental and forest industry sustainability by (Pulkki 2001): minimization of total cost, minimization of environmental impacts, maximization of

wood/fibre yield, maximization of wood/fibre value, maximization of wood/fibre quality, and maximization of benefits to society. There are numerous benefits of SCM. Jones (1999) found some typical improvements through proper application of SCM which are as follows: reducing the cost of supply chain 20-30%; reducing inventory 15-60%; and improving the performance of delivery 20-30%.

Sowlati (2009) introduced a forest products supply chain in which bioenergy production by using woody biomass feedstock is included. In this forest products supply chain the woody biomass harvesting, pre-processing, storage, chip procurement, pellet procurement and the flow of these materials are included. For example, harvest residues can be pre-processed (hauled to the roadside and chipped/ground) and chips can be directly sent to the conversion facilities (power plant), or before sending to conversion facilities woody biomass can be stored (Sowlati 2009). Sawmill residues (chips) can be directly supplied to the power plants for energy production or sawmill residues can be stored and then supplied to the conversion facilities when necessary (Sowlati 2009). Pellets can be prepared from sawmill residues in pellet plants and then pellets can be used as feedstock in power plants for energy production. Pellets can also be stored before using in power plants (Sowlati 2009). The SCM of Canadian forest sector should be flexible and should also be up-to-date depending on the current demand of the world market for forest products (Alam 2011; Alam *et al.* 2011).

In Canada, especially in northwestern Ontario, two main methods of forest harvesting are dominant, namely (1) full tree harvesting method (Figure 2) and (2) cut-to-length harvesting method. Woody biomass harvesting should be integrated with conventional forest harvesting to make the forest products supply including woody biomass from the Forest Management Units (FMUs) economically viable and environmentally sound. For the commercial point of view the tree species can be broadly categorized into two types, namely (1) currently merchantable trees or wood and (2) currently non-merchantable trees (Alam *et al.* 2009; Alam *et al.* 2011; Alam *et al.* 2012). These two groups are also necessary to be taken into account for the purpose of SCM of forest products in this region.

When full tree harvesting is applied in the forest of merchantable tree species forest product supply chain can be implemented by the following way. Trees are normally cut by using a feller buncher in this method. A grapple skidder is used to bring the felled trees to a roadside landing. At the roadside landing trees are delimbed and topped by using a stroke delimber. A slasher is used at the roadside landing to cut the log into required size. By this way four types of forest products are produced at the roadside landing in the forest, such as pulpwood, tree length, log assortment and slash. Pulpwood can be supplied to a pulpmill, tree length can be supplied to a sawmill/panel mill or a pulpmill, and log assortment can be supplied to a sawmill/panel mill. Slash is tops, branches and unmerchantable pieces of wood. At the forest roadside slash can be ground or chipped. By using chip trucks chips are transported to power plants to produce power. Ground biomass can be transported to power plants to produce power or to pellet plants to make pellets. At the forest roadside slash can be bundled by using a bundler. Bundles can be transported to a central processing centre, pellet plant or power plant yard. Loose slash can also be transported from a forest roadside landing to a central processing centre, pellet plant or power plant yard. At the central processing centre loose slash or bundles can be ground or chipped. Pellets can be prepared at the central processing centre. Chips and pellets can be supplied to power plants to produce power. Ground biomass can be transported to pellet plants or it can be supplied to power plants. The residue of a sawmill/panel mill can be used by the sawmill/panel mill itself for the production of heat and power. The surplus residue can be transported to a pellet plant or power plant. Similarly, the residue of a pulpmill can be used by the pulpmill itself for the production of heat and power. The surplus residue can be supplied to a pellet plant or power plant. Loose slash, bundle, ground biomass, or residue from a sawmill/panel mill or pulpmill can be used at a pellet plant to make pellets which can be supplied to a power plant to produce power. At a power plant yard bundled or loose slash can be processed to make ground biomass, chips or pellets. The produced ground biomass, chips or pellets can be used as feedstock at the power plant to produce power. Loose slash, bundles, ground biomass or chips can also be supplied to a biorefinery (Alam *et al.* 2009; Alam and Pulkki 2011; Alam *et al.* 2011; Alam *et al.* 2012). The residue from biorefinery can be used for power/energy generation (Figure 2).

When cut to length tree harvesting method is applied in the forest of merchantable tree species forest product supply chain can be implemented by the following way. Trees are normally cut, delimbed, topped and cut to specific length by a single grip harvester in this method. Slash is left on the forest floor as windrows. Pulpwood and log assortments are brought to a forest roadside landing by a forwarder. By using a special forwarder slash from forest floor can be brought to the forest roadside landing. Pulpwood and log assortments are transported to a pulpmill and a sawmill/panel mill respectively. The slash can be processed at the forest roadside landing or it can be transported to the destination from the forest roadside landing unprocessed. Loose slash, bundles, ground biomass or chips can also be supplied to a biorefinery. The residue from biorefinery can be used for power/energy generation. The further activities of the supply chain are same as in full tree harvesting method in the forest of merchantable tree species (Alam *et al.* 2009; Alam *et al.* 2011; Alam *et al.* 2012).

In full tree harvesting method in the forest of nonmerchantable tree species the tree cutting and hauling to the forest roadside landing are same as in full tree harvesting method in the forest of merchantable tree species. At a forest roadside landing trees are delimbed and topped by using a stroke delimber. A slasher is used at the landing to cut the log into required size. By this way there are three types of forest products are produced at the forest roadside landing, such as tree length, wood assortment and slash. Tree length and wood assortment can be supplied to a biorefinery. Slash can be processed as the same way as in other two previous methods. Loose slash, bundles, ground biomass or chips can also be supplied to a biorefinery. The residue from biorefinery can be used for power/energy generation. Further activities of the supply chain are same as in other two previous methods (Alam *et al.* 2009; Alam *et al.* 2011; Alam *et al.* 2012).

In cut to length tree harvesting method in the forest of nonmerchantable tree species trees are normally cut, delimbed, topped and cut to specific length of log assortments by a single grip harvester. Slash is left on the forest floor as windrows. Log assortments are brought to a forest roadside landing by a forwarder. By using a special forwarder slash from forest floor can be brought to the forest roadside landing. From the forest roadside landing log assortments are transported to a biorefinery by a log truck. Slash can be processed like in previous methods. Loose slash, bundles, ground biomass or chips can also be supplied to a biorefinery like in other methods. The further activities of the supply chain are same as in previous three methods (Alam *et al.* 2009; Alam *et al.* 2011; Alam *et al.* 2012).

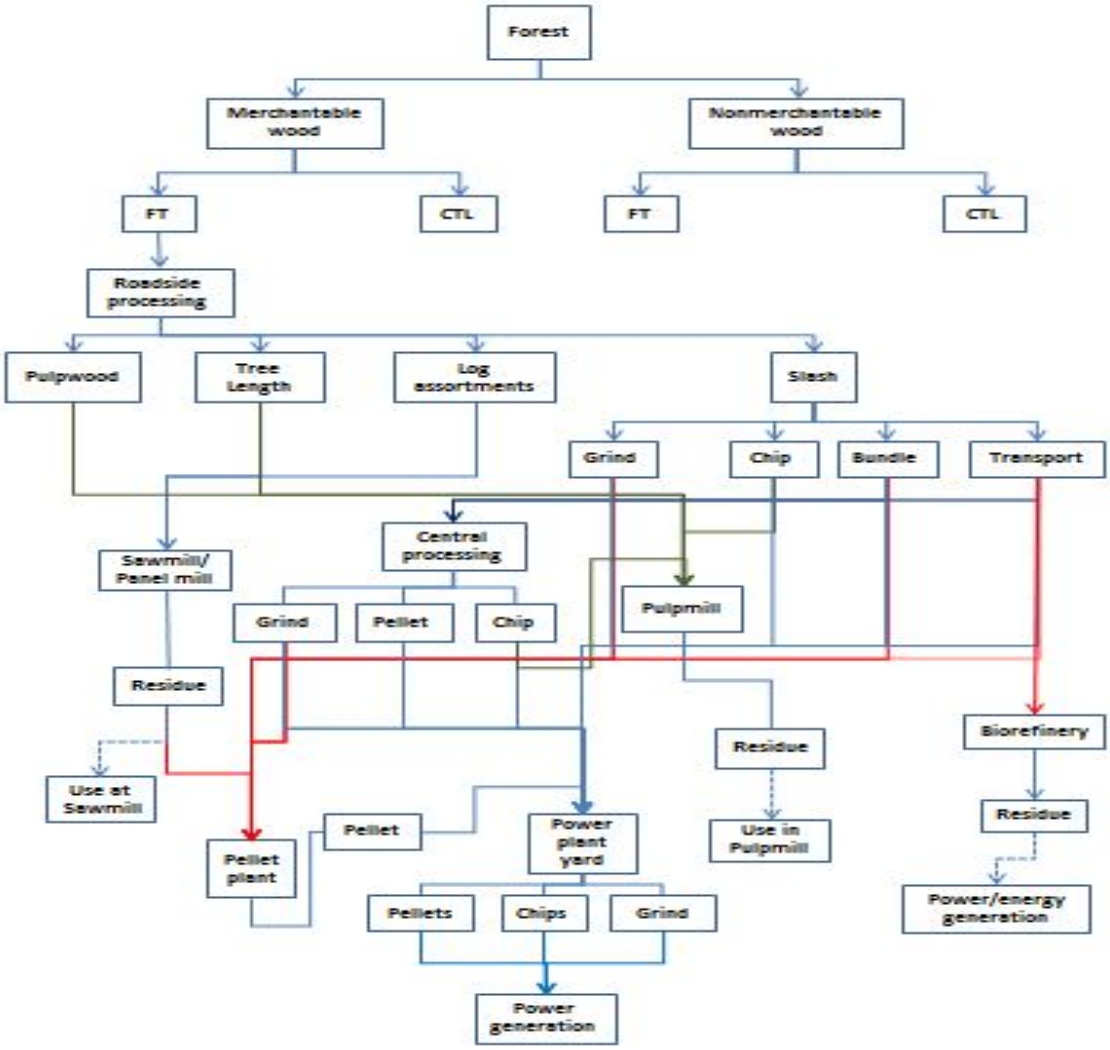

Figure 2: Harvesting of merchantable wood using full tree harvesting and resulting woody biomass for energy production options

3. Woody biomass supply chain for energy production

3.1. Major Sources of Biomass

The major sources of biomass for energy production are as follows: (1) Forest harvest residues, (2) Unutilized and underutilized wood, (3) Mill wood waste, (4) Landfilled wood waste, (5) Dedicated energy plantations, and (6) Municipal solid waste. All these major sources of biomass are briefly discussed as follows (Alam and Pulkki 2009; Bradley 2009).

3.1.1. Forest Harvest Residues

Forest harvest residues (FHR) represent the leftover of timber harvesting operations, such as tops, branches and unmerchantable parts of trees. In cut-to-length harvesting methods the FHR are left on the forest floor and in full tree harvesting methods FHR are left by the roadside of the forest as slash files. The estimated amount of FHR at roadside in Ontario is approximately 2.43 million oven dry tonne per year ($ODt \cdot yr^{-1}$) (Bradley 2009). By using a harvesting factor of 0.67, the annual average technical availability of FHR in FMUs in northwestern Ontario is about 2.1 million green tonne (gt) (Alam and Pulkki 2009; Alam and Pulkki 2011; Alam *et al.* 2012).

3.1.2. Unutilized and Underutilized Wood

Unutilized wood supply is the difference between the average annual available wood (m^3) and the actual average annual harvest of wood (m^3) in a particular forest. In Ontario the annual allowable cut (AAC) of roundwood was approximately 32 million m^3 in the year 2006, but out of which 22 million m^3 roundwood was actually harvested (FBI 2006). So 10 million m^3 was the unutilized wood supply in 2006 in the FMUs of Ontario. In 2010, out of 23 million m^3 AAC only 10 million m^3 roundwood was harvested in this province. In northwestern Ontario the annual unutilized wood supply in FMUs is over 4.5 million m^3 which corresponds the amount of biomass over 2 million $ODt \cdot yr^{-1}$ (FBI 2006; Bradley 2007). By using a harvesting factor of 0.67, the annual average technical availability of unutilized and underutilized wood (UUW) in FMUs in northwestern Ontario is about 7.6 million gt (Alam and Pulkki 2009; Alam *et al.* 2012).

3.1.3. Mill Wood Waste

In Canada around 78% of a typical sawlog is commoditized in the form of lumber (40%) and pulp and paper (38%), and the rest of the sawlog (22%) is mill residue in the form of sawdust, bark and shavings (FBI 2006; Bradley 2008; Bradley 2009). The amount of

residues produced by sawmills in Ontario is approximately 1.53 million ODt·yr^{-1}, out of which 1.08 million ODt·yr^{-1} is used as hog fuel. The amount of unused mill wood waste in Ontario is around 0.45 million ODt·yr^{-1}. The amount of mill wood waste as bark available in the year 2004 in northwestern Ontario was 430,000 m^3 (FBI 2006).

3.1.4. Landfilled Wood Waste

Landfilled wood waste is mainly available in the dumps of sawmills. The amount of landfilled wood waste in northwestern Ontario is approximately 105,000 ODt·yr^{-1}. Most of the landfilled waste is contaminated, and the moisture content of the landfilled waste is normally high. These factors may increase the recovery cost of landfilled wood waste for energy production (FBI 2006; Bradley 2008; Bradley 2009).

3.1.5. Dedicated Energy Plantations

Dedicated energy plantations are an important way in using biomass for energy production. In the USA and in many European countries dedicated energy plantations are raised for bioenergy production purpose. The common crops grown for energy production are elephant grass, switch grass, reed canary grass, willow, poplar etc. (FBI 2006; Bradley 2009). Fast growing willow plantations can be raised in Canada from which annually 5-10 ODt·ha^{-1} of biomass can be produced over 10-20 years (FBI 2006; Bradley 2009).

3.1.6. Municipal Solid Waste

Municipal solid waste can be used to produce bioenergy (Bradley 2008; Bradley 2009). For example, the City of Toronto spends 50.54 \$·t^{-1} for the haulage and disposal of waste. The amount of solid waste of this city is approximately 1.5 million t·yr^{-1} (City of Toronto 2005; FRI 2006). If the solid waste of the City of Toronto can be used for the energy production the city can save money in garbage disposal and also can help maintain clean environment.

3.2. Forest Residue Supply Chains

There are different types of woody biomass available in the forest. These are categorized into four main classes as follows: (i) FHR; (ii) small trees and slash from thinning and cleaning; (iii) wood affected by fire, storm and insect; and (iv) unmerchantable wood. FHR is the primary source of forest biomass as it is already available on the ground. There are many supply chain options of FHR. The following are the major options of FHR supply chains (Bradley 2007; Ranta 2007).

3.2.1. Terrain Chipping

A mobile chipper is used in the harvesting area to chip the slash; a small container is used to collect the chips; and the chip container is brought to the roadside. The chip containers are loaded to the truck at the roadside, and the truck hauls the chips to the power plant or other destination (Bradley 2007; Ranta 2007).

The major strengths of terrain chipping are: same unit of chipping and forest haulage is used; harvesting sites are small; storage space of residues is small; and storage areas are cleaned after harvesting operations (Kärhä 2005; Kärhä 2007). Terrain chipping has some weaknesses including the following: it is ineffective; harvesting sites are uneven; container size of chipper is an issue; forwarding distance is long; storage areas are uneven and muddy; breakdown problem; and interruption due to winter conditions (Kärhä 2005; Kärhä 2007).

3.2.2. Roadside Chipping

In the full tree harvesting method the FHR is available at the roadside as slash. In the cut-to-length operation trees are delimbed on the forest floor and the residue is forwarded to roadside. A truck mounted chipper or a mobile chipper is used to chip the slash at roadside and the chips are transferred to a truck (Bradley 2007; Ranta 2007).

When in roadside chipping separate chipper and chip truck are used, the operation becomes flexible. Moreover, there has been huge experience in roadside chipping and modern harvesting machinery is available for this system (Kärhä 2005; Kärhä 2007). However, there are some drawbacks in this system including following: the supply chain is hot; machine utilization rate is not always optimal; for raw materials of chipping a large roadside storage space is required; the storage areas are small and muddy for the machines; and the roadside storage areas become untidy after harvesting operations (Kärhä 2005; Kärhä 2007).

Roadside chipping by integrated chipper-chip truck has some advantages including following: in this system same unit is used for chipping and long-distance transportation; no hot supply chain is required; chips can be used by several plants; and harvesting sites are small (Kärhä 2005; Kärhä 2007). However, it has also some disadvantages including following: load size is small; transportation distance is long; transportation cost is high; it needs a large roadside storage for raw materials; and after harvesting operations the roadside storage areas become untidy (Kärhä 2005; Kärhä 2007).

*3.2.*3. Terminal Chipping

A terminal is normally situated at a short distance from harvesting site. The uncomminuted FHR is transported to the terminal. In terminal loose slash and/or bundled slash are chipped. Bundles are composite residue logs which are created by compressing uncomminuted slash either on the forest floor or at roadside using a mobile bundler. A standard logging truck is used to transport these composite residue logs to the terminal. Normally a large bulk truck is used to transport the chips from the terminal to the next destination/power plant (Bradley 2007; Ranta 2007).

Terminal chipping is an efficient system as no hot chain is required and the chipping operation is perfectly managed in this system. Other positive points of terminal chipping are: effective comminution; secured chip delivery; chips supply to several small plants; running plants with small storage fields or stocks sustainably; opportunity to keep harvesting sites small; and chipping during winter. However, identification of appropriate terminal areas is tricky, establishment cost of a new terminal is high and extra handling time is required in this system. Hence total supply chain costs are relatively high in terminal chipping system (Kärhä 2005; Kärhä 2007).

3.2.4. Chipping at Power Plant

Loose slash and/or bundled slash are transported from the forests to the mill yard where these will be comminuted (Bradley 2007; Ranta 2007). Loose slash is normally used when the total supply chain has a relatively short transportation distance. The use of bundled slash is economically feasible in this system when long distance transportation is necessary (Kärhä 2005; Kärhä 2007).

Chipping at power plant does not need to use hot chain. Using loose slash for chipping at power plant is the most cost efficient system as large-scale production can be done by powerful comminution. However, transportation cost becomes high when long distance transportation is used. Moreover, a large storage field at the plant is required in this system (Kärhä 2005; Kärhä 2007). By chipping bundles at power plants large-scale production is possible by effective comminution. In this system long distance transportation can be kept economically feasible and the comminution cost is also low. By applying bundling system roadside storage space can be kept small and forest haulage can be made effective and cost competitive. However, the bundling cost is high and bundling strings when slow speed crushers are used (Kärhä 2005; Kärhä 2007).

3.4. How to Transport Biomass Cost Effectively

3.4.1. Modes of Biomass Transport

Biomass can be transported by four modes of transport, namely pipe, truck, train and ship. The most widely used mode of transportation in the biomass supply chain for energy production is the truck-based transport. Ship is also used to transport biomass (Short 2009). It is necessary to explore the economical ways of biomass transportation to make the biomass supply chains for energy production economically feasible and sustainable.

3.4.2. Biomass Transportation by Truck

On average the energy density of biomass is less than the energy density of fossil fuels (Ashton and Cassidy 2007). In comparison with fossil fuels a larger amount of biomass needs to be transported to produce a unit of power. The infrastructure to transport fossil fuel (e.g., coal and petroleum) can be streamlined to the fuel, such as coal trains and pipelines because fossil fuels have concentrated extraction points (e.g., wells and mines).

Biomass transportation for energy production is mainly dependent on truck transport because of the requirement of collecting low volumes of biomass from locations distributed over large areas to supply biomass feedstock to an energy plant. At present the size of a biomass truckload (ground/chips) is 20-40 gt (Short 2009). For the short transport distances, truck transport is the most economical mode of biomass transportation. The dependence on truck transport makes the cost of woody biomass transportation per unit (e.g., $\$\cdot gt^{-1}\cdot km^{-1}$) to large scale biorefineries more expensive than the transport of fossil fuels especially when the transportation distance is long (Mahmudi and Flynn 2006; Yemshanov and McKenney 2008).

*3.*4.3. Biomass Transportation by Pipeline

Kumar *et al.* (2004) conducted one research on the pipeline transport of mixed hardwood and softwood chips from western Canada. In this pipeline two carrier fluids were used, namely water and heavy gas oil. They explore that for transport distance from100 to 500 km and for the flows of around 2 million $ODt\cdot yr^{-1}$ (large flows) the pipeline transport cost of biomass is less than truck transport. They found on average pipeline transport costs for a 100 km distance 15 $\$\cdot ODt^{-1}$, and for a 500 km distance 40 $\$\cdot ODt^{-1}$, respectively.

Though for cellulosic ethanol production pipeline could be used but it is not a feasible way for using biomass feedstock for the purpose of combustion in a boiler to produce power because during pipeline transport the water content of chips is increased by13%, and chips absorb oil approximately 50% of their weight, and hence the fuel quality is deteriorated at that time (Ashton and Cassidy 2007). So, pipeline transport is not a viable alternative to truck transport in transporting biomass feedstock to the power plant for the production of energy by direct combustion (Short 2009).

3.4.4. Biomass Transportation by Rail

In rail transport system of biomass transportation trucks would be used to bring biomass from the field to the nearest train station, after which the train would transport biomass to the destination. There are two types of costs in transportation: i.e., fixed cost and variable cost. Fixed cost is independent of transport distance and variable cost is dependent on the distance a unit is transported. Variable cost has a linear relationship with fuel, wage and capital recovery costs. The fixed cost for rail is higher (27-28 $\$\cdot ODt^{-1}$) than the fixed cost for truck (5 $\$\cdot ODt^{-1}$). The variable cost for rail is less (0.03 $\$\cdot ODt^{-1}.km^{-1}$) than the variable cost for truck (0.11- 0.13 $\$\cdot ODt^{-1}\cdot km^{-1}$) because rail is much more fuel efficient than truck (Mahmudi and Flynn 2006; Short 2009).

Truck transport for transporting woody biomass from FHR for energy production is cost competitive up to a distance of 125 km. After that distance the rail transport of woody biomass becomes cheaper than truck transport of woody biomass (Short 2009). The rail lines are limited within certain geographic areas in North America while road networks cover most of the areas of North America. For transporting biomass to the long distance for medium to large bioenergy plants rail transport can be coordinated with truck transport, but for short distance transport to small energy plants rail transport is not a viable option (Kumar *et al.* 2003; Mahmudi and Flynn 2006; Short 2009).

3.5. Woody Biomass Supply Chain Experiences

*3.5.*1. Woody Biomass Supply Chains in Sweden

In Sweden research on various biomass supply chains for energy production has been conducted over a last couple of decades. During this time many biomass supply chains have been tested, rejected and improved in this country. At present the most successful biomass supply chain in Sweden is roadside chipping. McCloy *et al.* (2007) described the chips procurement costs ($\$\cdot MWh^{-1}$) from FHR for energy production found in 13 studies from 1982 to 2003 in Sweden. The biomass procurement costs have fallen 1.9% annually, from 27 $\$\cdot MWh^{-1}$ in 1980-82 to 15-17 $\$\cdot MWh^{-1}$ in 2000-03 (Bradley 2007).

In the FHR supply chains felling costs are associated with primary forest products. So the main cost factors in the supply chain of FHR for energy production are: forwarding, chipping, transportation and stumpage (Bradley 2007; McCloy *et al.* 2007). At present in Sweden the operators know how to harvest primary forest products and forest biomass in an effective and efficient way. During harvesting operations they avoid driving over residues. They keep the residues as piles near to sawlog and pulpwood. So the

contamination of woody biomass is reduced. In Sweden new forwarders have been invented which are used to forward the slash in an economically feasible way. Slash is collected by the creaming off the top of the slash by the forwarders. By this way the maximum nutrients of slash are kept on the forest floor, forwarding time of slash is reduced, and the forwarding costs are minimized. In Sweden comminution of slash by chipping is cheaper than by grinding. But the chippers need more maintenance if the FHR is contaminated by rocks. In this country the chipping costs have been reduced significantly by developing better chipping technology and by reducing the contamination of FHR. The machine downtime has been reduced, and production capacity has been increased over time. The transportation costs are almost stable. Container trucks are widely used to transport chips. The stumpage (a cost factor) is paid by the forest owners as a fee (Bradley 2007).

Table 1 shows the total supply chain cost reduction of roadside woody biomass chipping for energy production over the years from 1983 to 2003 in Sweden (Bradley 2007). The cost reduction in the roadside chipping system of woody biomass supply chain over twenty years was 32% and the average annual cost reduction was 1.94%. The cost reductions in forwarding, chipping, transportation, and stumpage and others were 58%, 33%, 15%, and 11%, respectively (Table 1).

Table 1: Biomass supply chain costs of roadside chipping for energy production (Bradley 2007)

Cost factor	Chipping cost in 1983 ($.GJ^{-1})	Chipping cost in 2003 ($.GJ^{-1})	Cost reduction in 2003 (%)	Annual cost reduction (%)
Forwarding	1.98	0.84	58	
Chipping	2.32	1.56	33	
Transportation	1.51	1.28	15	
Stumpage and other	1.17	1.05	11%	
Total	**6.99**	**4.72**	**29**	**1.62**

In Sweden biomass supply chain costs have been reduced by doing continued research on biomass-based energy production technology and networking. The production rate of biomass feedstock for energy production has been increased as a result of learning by doing and eventually by using modern technology. On average 13% cost reduction was experienced in woody biomass supply chain for energy production for each production doubling (Bradley 2007).

3.5.2. Woody Biomass Supply Chains in Finland

There have been many studies on woody biomass supply chains for energy production in Finland. The remarkable research has been done on residue chipping, bundling, transportation, and terminals.

In one study done in 2005 in Finland the total supply chain costs of three systems were compared (Karha and Vartiamaki 2006; Bradley 2007). The three systems are: roadside chipping, bundling and loose residues. Generally in comparison with other systems bundling system is the most costly especially when the haul distance is short. The bundling system can be optimized by applying following measures: better residue layout, operator training, increasing bundle size, and higher slash density per ha. By applying optimized bundling system total supply chain costs can be reduced from \$11.44/m^3 to \$7.87/m^3 (30% reduction) (Karha and Vartiamaki 2006; Bradley 2007). When the hauling distance is more than 60 km the optimized bundling supply chain is the most economical woody biomass supply chain in Finland. For short hauling distance loose residue supply chain is the most competitive, but when distance increases the cost of this supply chain becomes higher.

Ranta (2007) conducted one study on the supply chains of woody biomass for energy production in Finland. He compared the total supply chain costs of five systems, such as (i) stumps, loose, (ii) energy wood, chips, (iii) logging residues, chips, (iv) logging residues, logs (bundles), and (iv) logging residues, loose. This study indicates that the highest cost biomass supply chain is stump, loose system followed by energy wood, chips. The woody biomass supply chain of bundling system is cheaper than the first two systems. The costs bundling system and the logging residues, chips system are almost similar. Recently logging residues, loose system has become the cheapest woody biomass supply chain system for energy production due to use of large 160 m^3 trucks to transport loose residues. In logging residue, logs (bundling) system the size of each log is 0.4-0.5 m^3 and one truckload contains maximum of 60 composite logs. The trend shows that the bundling system will become the cheapest supply chain system of woody biomass for energy production when the hauling distance is more than 60 km and the equipment of this system is improved (Ranta 2007; Bradley 2007).

Terminal comminution can solve many problems of biomass supply chains for energy production. It can be used as a buffer storage area for both the biomass supplier and biomass user. It can prepare woody biomass feedstock according to the requirement of power plant. When chippers in field breakdown, chip trucks can be loaded at the terminal. When power plant does not receive any biomass feedstock at that time the biomass feedstock (e.g., chips) prepared at roadside landing of forest can be transported to the terminal (Johansson *et al.* 2006; Bradley 2007).

One study conducted by Johansson *et al.* (2006) in Finland compares the costs of biomass supply chains options, such as one option without a terminal and four options with a terminal (Bradley 2007). Out of four options of terminals the option number 4 has the lowest cost. In this option the terminal is closer to the biomass source, not to the power plant and in terminal chipping is conducted, not at landing. In comparison with biomass supply chain without a terminal the biomass supply chain with a terminal is more costly (Johansson *et al.* 2006; Bradley 2007) because extra unloading, handling and reloading costs are necessary to be added in the terminal system. But when we consider the efficiency of energy production by using biomass feedstock in a sustainable way terminal is essential in biomass supply chain. For example, power plant downtime can be minimized by efficient chipping at the terminal.

*3.5.*3. Bundling in USA

The USA implemented the Healthy Forest Restoration Plan and the National Fire Plan which have made a big amount of FHR available for energy production. In one study on bundling of residues from forest thinning in the USA shows that the supply chain cost of this system was 19-24 \$US·ODt^{-1} (Rummer *et al.* 2004; Bradley 2007).

In one study on the bundling system of woody biomass supply chain in the USA, data was collected from eight locations in California, Oregon, Idaho and Montana. This study explores that it is not economically feasible to collect all the residues which are scattered in the forests. The characteristics of the best bundles are: bundling with alternating butts and tops, slash of various lengths, and residues are not too dry. Timberjack Bundler was used in bundling operation. Specifications of this machine were 10-30 bundles per hour (bundles·h^{-1}). The average bundling rate of this machine was found 20 bundles·h^{-1} (8 ODt·h^{-1}) during study time. The costs of operation were as follows: (i) the owning cost of the machine was 58 \$·SMH^{-1}, (ii) operating costs including fuel, lube, repair and maintenance were 50 \$·SMH^{-1}, and, (iii) labour cost was 22 \$·SMH^{-1}. The total cost was 130 \$·SMH^{-1}. Table 2 shows that the average supply chain cost of FHR supply chain for energy production by using bundler in USA is 31.50 \$·ODt^{-1}. In this supply chain cost, stumpage and profit margins are not included (Rummer *et al.* 2004; Bradley 2007; Bradley 2009).

Table 2: Biomass supply chain costs in the bundling system of FHR in the USA (Rummer *et al.* 2004; Bradley 2007)

Activities	**Costs of supply chain activities**		
	Low (\$·ODt^{-1})	**High (\$·ODt^{-1})**	**Average (\$·ODt^{-1})**
Collect and Bundle	16	16	16
Forwarding	5	5	5
Haul 80 miles	5	10	7.5
Chip at plant	3	3	3
Total supply chain cost (\$·ODt^{-1})	**29**	**34**	**31.5**

3.6. Biomass Supply Chains in Canada

3.6.1. Chipping and Grinding Roadside Slash

Canada has long time experience with supply chains to supply chips to pulp mills by chipping full-tree in forests (Bradley 2009). FPInnovations FERIC Division has been conducting research on chipping and grinding slash for the purpose of producing energy by using woody biomass feedstock in different parts of Canada for several years (Ryans 2008). In Canada 95% of forest harvesting is full tree. So in this country at forest roadside approximately 95% of FHR is available.

Table 3 shows the results of one FPInnovations FERIC Division's field testing on the supply chain costs (\$·ODt^{-1}) of roadside FHR from full-tree harvesting method for energy production in Ontario (Ryans 2008; Bradley 2009). In this test grinders were used to grind the FHR at roadside. Three cases were developed in this study, such as optimistic, realistic, and pessimistic. In the optimistic case the following assumptions were taken: license charge was low, grinding rate was 30 ODt·h^{-1}, and transport distance was 50 km. In the realistic case the following were assumed: pre-piling of slash was arranged with harvesting operation, there were charges for using road and other forest management activities, grinding rate was 25 ODt·h^{-1}, and the transport distance was 100 km on highways, primary roads, secondary roads and tertiary roads. In the pessimistic case the following assumptions were taken: there was no integration of pre-piling with harvest operations, due to tertiary roads graveling extra road charges were required, the grinding productivity was low, and the transport distance was 150 km. Table 3 shows that the total supply chain costs were in the optimistic case 24.11\$·ODt^{-1}, in the realistic case 43.60 \$·ODt^{-1}, and in the pessimistic case 61.54 \$·ODt^{-1}, respectively (Ryans 2008; Bradley 2009).

Table 3: Biomass supply chain cost in the roadside FHR grinding system in Ontario (Bradley 2009)

Activities	**Roadside FHR recovery costs**		
	Optimistic 50 km (\$·ODt^{-1})	**Realistic 100 km (\$·ODt^{-1})**	**Pessimistic 150 km (\$·ODt^{-1})**
Pre-piling	2.64	2.64	0
Comminution (grinding)	10.25	13.04	18.56
Transport	12.4	21.51	30.02
Stumpage	0	0	0
Road improvement	1	3	7.96
Planning and supervision	1	2.25	2.25
Overhead	0	2.25	2.25
Compliance	0	0.5	0.5
Silviculture Rebate	-3.18	-1.59	0
Total recovery cost (\$·ODt^{-1})	**24.11**	**43.6**	**61.54**

3.6.2. Bundling in Canada

In Canada many bundling trials have been conducted in several locations (Bradley 2007; Ryans 2008). FPInnovations FERIC Division conducted some bundler trials to supply woody biomass for energy production. The results on bundling trials found in Canada were almost similar to the results on bundling trials in the USA (Bradley 2007; Ryans 2008; Bradley 2009). Table 4 shows the full supply chain costs (\$·ODt^{-1}) of FHR for energy production by using bundler in Canada. The table shows that the supply chain cost of FHR for energy production in estimated achievable cost of bundling with a 100 km transport is 51.14 \$·ODt^{-1}.

Table.4: Biomass supply chain cost in the bundling system of FHR in Canada (Bradley 2007)

Activities	**Costs of supply chain activities**		
	50 km (\$·ODt^{-1})	**100 km (\$·ODt^{-1})**	**150 km (\$·ODt^{-1})**
Collect and Bundle	17.2	17.2	17.2
Forwarding	5.38	5.38	5.38
Haul	13.46	17.15	19.16
Chip at plant	5	5	5
Sub-total (\$·ODt^{-1})	41.04	44.73	46.74
Forest Management	4	6.41	6.41
Stumpage	0	0	0
Total supply chain costs (\$·ODt^{-1})	**45.04**	**51.14**	**53.15**

3.6.3. Learning Curves of Biomass Supply Chains

The supply chain costs of woody biomass for energy production should be improved over time. The supply chain costs can be reduced over time by applying certain measures, such as learning by doing, improving technology, increasing production rate, etc. (Bradley 2007). Generally the overall costs of the supply chains decline at a slower rate over time (Figure 3). Sweden and Finland already reduced the supply chain costs of chipping residues by conducting continued extensive research for decades.

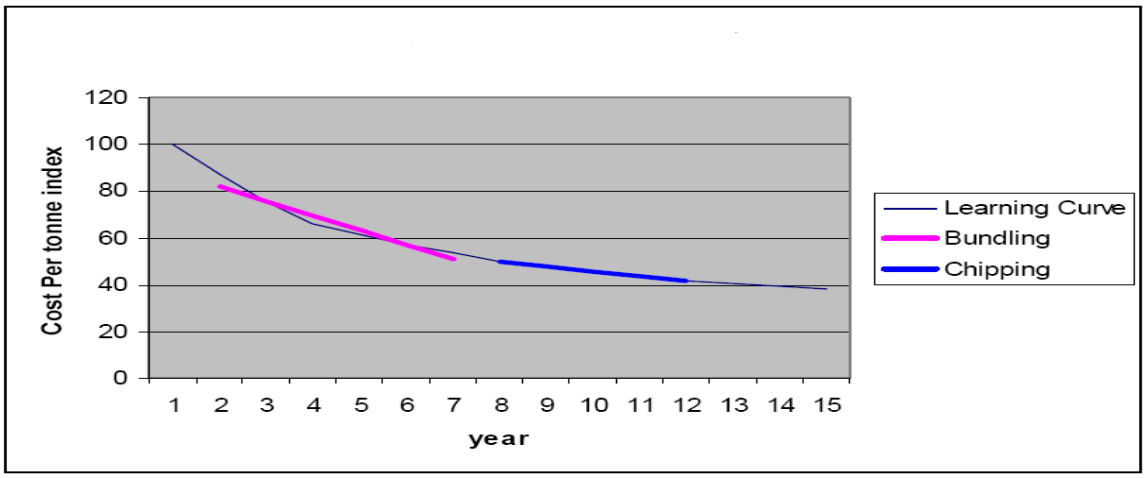

Figure.3: Learning curves of woody biomass supply chains (Bradley 2007)

Though in Canada the research on biomass supply chain for energy production is not so old Canada can benefit by using the experience of Sweden and Finland to improve the roadside grinding/chipping system of biomass supply chain (Bradley 2008; Alam and Pulkki 2009). Therefore, the roadside FHR grinding system of woody biomass supply chain is almost down the learning curve. So cost reduction would be slow in this system. Bundling system of biomass supply chain is new and higher up the learning curve (Figure 3). So in this system the significant amount of cost reduction would be expected because at the early stage of learning curve the cost reduction is normally higher than at the later stage of this curve (Bradley 2007; Ryans 2008; Alam and Pulkki 2009; Bradley 2009). If integrated bundling of FHR with the forest harvesting is implemented it would be expected that bundling system of woody biomass supply chain for energy production will be one of the most economically viable modes of woody biomass supply chains in Canada.

4. Influence of wood properties on woody biomass supply chain

4.1. Wood Density

Wood density is the mass per unit volume of wood (e.g. gm/cm^3, kg/m^3, t/m^3, lb/ft^3 etc.). As 1 m^3 volume of pure water has 1,000 kg mass the materials which are under 1,000 kg/m^3 float in water and which are denser than water (i.e., with a specific gravity of more than 1) sink in water. By keeping pure water as the base line (specific gravity of water = 1) the specific gravity is the comparison of density of other materials either lighter or heavier. As specific gravity does not have any unit, it is just a comparison of densities specific gravity of wood can be applied across any units (Simetric 2009).

In general the denser wood has the higher heat value. Hosegood *et al.* (2009) conducted one research on wood properties of tree components of seven tree species commonly available in northwestern Ontario. The species are as follows: black spruce, balsam fir, jack pine, tamarack, white birch, trembling aspen and black ash. They found that within the same species different tree components have different specific gravity. For example, upper bark of poplar has the highest specific gravity among the tree components of this study, i.e., 0.84, and the specific gravity of lower bole of poplar is 0.48. On average barks have the highest specific gravity, bole has the lowest specific gravity, and branches are in between barks and bole in specific gravity. They also found that within the same species different tree components have different gross heat values. In this study lower bark of white birch shows the highest gross heat value, i.e., 26 MJ.kg^{-1}, and the gross heat value of upper bark of birch is the second highest, i.e., 24 MJ.kg^{-1}. On average barks show the highest heat value. But the barks of black ash species show the lowest heat value (18 MJ.kg^{-1}).

Though on average more dense wood shows the higher heat values but there is no guarantee that always higher heat value of biomass can be obtained from the species with more wood density. Even different components of a tree do not always follow the same trend of wood density and heat value. For example, if we compare only branches for the specific gravity and heat value we see that the branch of black ash has the highest specific gravity (0.7), but the branch of black ash has the lowest gross heat value (19 MJ.kg^{-1}) (Hosegood *et al.* 2009). So not only density, also we have to take into account the influence of other properties of wood on utilizing forest biomass.

4.2. Moisture Content

The moisture content available in woody biomass plays an important role on the production of energy by using woody biomass feedstock. The moisture content varies greatly in woody biomass feedstock. The range of moisture content in freshly cut wood may be 22 to 67% (Macmillan 2001). Woody biomass contains on average 37.2% moisture. Moisture content varies depending on species, age, tree components etc. Generally softwood contains more moisture (46.1%) than hardwood (30.2%), young tree contains more moisture than older tree, sapwood contains more moisture than heartwood, and foliage contains more moisture than bole (Macmillan 2001).

Climatic conditions, harvesting time, and the duration and method of woody biomass storage influence the moisture content in woody biomass feedstock. Lower moisture in woody biomass means the higher quality feedstock to generate heat and power by

combustion in boiler because net calorific value of woody biomass feedstock is increased when moisture content of it is reduced. Many woody biomass based generating stations are designed by setting the moisture content of woody biomass feedstock to be used for producing energy because net heating value of wood, ignition properties and combustion efficiency process are greatly influenced by the moisture content (Macmillan 2001).

Moisture content of woody biomass feedstock increases the net heat value decreases and ultimately combustion cannot be sustained when the moisture content increased to a point (approximately 67%) which is called black out zone (Macmillan 2001). Another serious influence of increasing moisture content is its effect on ignition. High moisture content in woody biomass causes the more energy requirement for ignition of combustion as more energy is required to evaporate the inherent moisture of woody biomass feedstock to start combustion process. Hence high moisture content creates energy inefficiency (Macmillan 2001).

For dry cellulose material 0.145 $kW \cdot kg^{-1}$ energy is required to obtain ignition at 302^0C, and approximately 3.269 $kW \cdot kg^{-1}$ net heat is produced. For cellulose material with 50% moisture content, 0.425 $kW \cdot kg^{-1}$ energy is required to obtain ignition at 315^0C, and only 1.084 $kW \cdot kg^{-1}$ net heat is produced (Cassidy and Ashton 2007; Macmillan 2001). It is revealed that moisture content influences the utilization of biomass the most when we take into account all factors involved with moving and utilizing the biomass.

Wood needs to be seasoned before using as woody biomass feedstock for energy production. Approximately 10-15% moisture is reduced if felled trees are left in the forest for one summer. During that time needles of felled trees drop off which reduce the risk of corrosion in boiler during combustion of woody biomass feedstock and the nutrients of trees are retained in the forests (Kofman 2009). If round wood is stored as covered pile at the roadside or in yard for one summer approximately 30% moisture content of woody biomass is reduced. In this way by natural drying the moisture content of woody biomass can be reduced to the level of 20% (Kofman 2009).

When ground woody biomass is stored, immediately its biological degradation starts. If more moisture content and nutrients are available in the crushed/ground woody biomass the faster degradation of it is observed. Carbon dioxide, water and heat are produced by degradation. Dry matter loss is the common phenomenon of ground biomass storage. The pile of ground biomass from freshly harvested conifers heats up to 70-80^0C very quickly. So if the pile of ground woody biomass is very large with height more than 12 m there is a risk of spontaneous combustion (Kofman 2009).

To minimize the degradation of woody biomass by biological activities the moisture content should be kept below 30%. Ground woody biomass can be stored for a few months if the moisture content is below 40%. If the moisture content is over 40% the woody biomass should be burnt immediately. The rate of dry matter loss of ground biomass prepared from freshly harvested conifers with needles is 2-3% per month in storage. The dry matter loss of woody biomass in storage is minimal if it is dry (Kofman 2009). The effective heating value ($MJ \cdot kg^{-1}$) of woody biomass decreases if the moisture content of wood increases. This is true for all tree components and also for all tree species (Nurmi 1993).

The transportation cost of woody biomass feedstock for energy production increases when the moisture content of woody biomass increases. The moisture content increases the volume and weight of biomass. Vehicles have limited space for transporting materials. In Ontario, the vehicles have to follow the weight limits specified by the Ontario Ministry of Transportation (MTO. 2009). So if the woody biomass contains the higher moisture contents the lower amount of biomass can be transported. It makes the woody biomass transportation costs high.

As discussed earlier many bioenergy plants use the boilers setting with certain moisture content limits. If moisture content of woody biomass feedstock increases the efficiency of boiler decreases. Hence the cost of bioenergy production by using woody biomass feedstock increases (Macmillan 2001; Cassidy and Ashton 2007). So the moisture content of woody biomass must be minimized to minimize the bioenergy production cost and ultimately to maximize the profit of bioenergy production.

4.3. Ash Content

Ash content can be defined as the amount of solid wastes after complete combustion of wood (Huhtinen 2005). Ash is produced by the chemical breakdown of woody biomass. The ash produced by the combustion of woody biomass feedstock for energy production is a standard parameter for fuel measurement. Heating value of fuel is reduced if ash content of woody biomass is high. Huhtinen (2005) found the range of ash content in woody biomass from 0.08 to 2.3 %. Study conducted by Hosegood *et al*. (2009) explores the ash percentage in different components of seven common tree species of northwestern Ontario (Figure 4). The study shows the highest ash percentage in black ash species, especially in lower bark, leaves and upper barks. On average barks and leaves have the highest percentage of ash, lower bole and upper bole have the lowest percentage of ash, and branches are in between in ash concentration (Hosegood *et al.* 2009).

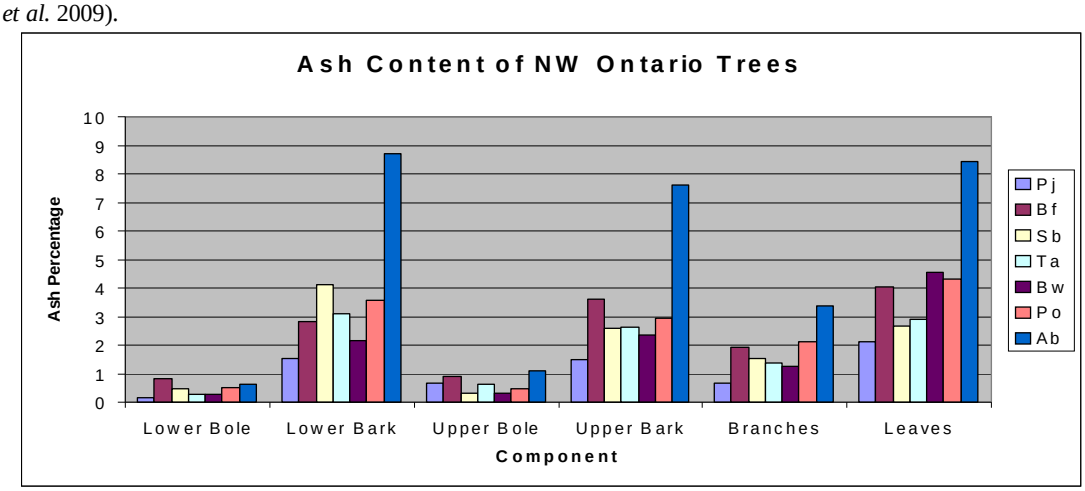

Figure 4: Ash contents of tree components of northwestern Ontario tree species (Hosegood *et al.* 2009)

The chemical composition of ash makes handling and processing of woody biomass difficult during thermo-chemical conversion, especially during combustion. Sometimes at high temperature slag is created by the reaction of ash which can reduce the rate of power generation of the plant (McKendry 2001).

4.4. Chemical Composition

Wood is composed of different types of chemical substances. Three basic polymers are present in woody biomass, such as cellulose, hemicelluloses and lignin; several mineral components are also available in woody biomass (Macmillan 2001). The major components of woody biomass are: cellulose ($C_6H_{10}O_5$), hemicelluloses ($C_5H_8O_4$) and lignin ($C_9H_{10}O_3(OCH_3)_{0.9\text{-}1.7}$) (Macmillan 2001; Cassidy and Ashton 2007). The chemical composition and energy value of some tree species are shown in Table 5. Cellulose is a high molecular weight polymer composed of glucose (sugar) chains. The elements of the chain are carbon, hydrogen and oxygen. Cellulose comprises nearly 50 percent of woody plant mass. It is insoluble in water, petrol, alcohol, ether and benzene, and soluble in hydrochloric and sulphuric acids. Hemicelluloses are polymeric units that are comprised of pentose sugar carbohydrates. When reacted with acids they produce different types of sugar. They comprise 25- 35 % wood. Lignin is a phenylpropane polymer which exists mainly as an intercellular material in woody biomass to hold the cellulose and hemicelluloses components together. It comprises 15- 25 % of woody biomass. It is a high energy content component of woody biomass (Macmillan 2001).

Table 5: Chemical composition and energy value of some tree species (Macmillan 2001)

Tree species	Cellulose (%)	Lignin (%)	Hemicelluloses (%)	Energy ($GJ\cdot t^{-1}$)
Beech	45.20	22.10	32.70	19.67
White birch	44.50	18.90	36.60	19.38
Red maple	44.80	24.00	31.20	19.54
Eastern white cedar	48.90	30.70	20.40	19.54
Hemlock	45.20	32.50	22.30	20.67
Pine	45.00	28.60	26.40	20.77
White spruce	48.50	27.10	21.40	20.68

There are several mineral elements in woody biomass. Carbon, oxygen and hydrogen are the principal elements. Normally, the concentration of these elements is higher in hardwood species than in softwood species. They affect the energy content, though they do not produce energy during combustion. The site of the forest is more responsible than the age, species, or size of the tree for the concentration of these mineral elements (Macmillan 2001).

Other elements also present in woody biomass, such as nitrogen, chlorine, sulfur and heavy metals. The effects of these elements during woody biomass combustion for energy production are described as follows (Cassidy and Ashton 2007). Nitrogen is oxidized into nitrogen oxide (NO_x) during combustion as a component of fuel system. High level NO_x emission from combustion increases the acidification of soils and water, though low level emission of NO_x may be helpful for forest fertilization. Chlorine is available in foliage. It can form alkali compounds with potassium and sodium which create oxidation and corrosion which is harmful for boiler equipment during woody biomass combustion. To minimize the risk of corrosion foliage from woody biomass should be removed. Sulfur emission is harmful for the ecosystem. Sulfur oxide (SO_x) is formed during combustion by oxidization with nitrogen which causes soil acidification and water acidification. Ultimately the environment will be destroyed by this affect. During combustion, some heavy metals vaporize and the rest form ash. When in ash the percentage of heavy metals is high ash should not be recycled as a fertilizer because when metals leach into groundwater crops may absorb metals.

Other components of woody biomass are: polyphenolics, tannins, resins, waxes, gums, coloring agents etc. They are normally known as volatiles, and they comprise approximately 5-30 % of woody biomass (Macmillan 2001). There are some minor constituents also, such as silica, potassium, calcium and phosphate which comprise approximately 0.1-3% of woody biomass (Macmillan 2001; Cassidy and Ashton 2007).

The chemical composition and heat value of woody biomass vary from species to species. In general the average proportions of materials concentration in softwood species are: cellulose 43%, hemicelluloses 28%, and lignin 29%. In hardwood species the average proportions of chemicals are: cellulose 43%, hemicelluloses 35%, and lignin 22% (Macmillan 2001).

The heating value of woody biomass varies depending on its chemical composition. Differences in tree components within a tree have significant effect on the thermal value ($MJ\cdot kg^{-1}$) of wood due to the differences in chemical composition of wood. Cellulose and hemicelluloses, together, are known as holocellulose. Lignin has higher calorific values than holocellulose (Table 5). For example, in woody biomass of Douglas fir the heat value of holocellulose is 4.853 $kW\cdot kg^{-1}$, and the heating value of lignin is 7.402 $kW\cdot kg^{-1}$. Volatiles play important roles on heating value of woody biomass. They normally contain high heating value up to 9.672 $kW\cdot kg^{-1}$. Heating value of woody biomass increases if the lignin and volatile contents of wood species increase (Macmillan 2001).

The major wood components are carbon, hydrogen and oxygen. Carbon and hydrogen are combustible. Oxygen is non-combustible but it helps woody biomass combustion. Lignin and resins have a higher heating value than cellulose and hemicelluloses because first two elements are rich in carbon and hydrogen (Nurmi 1993).

4.5. Thermal Values

The thermal value of wood is the amount of energy or heat released when it is burnt in air. The thermal value is measured as energy content per unit mass, e.g., $MJ\cdot kg^{-1}$ or $GJ\cdot t^{-1}$. It can be expressed in two ways, such as gross thermal value or higher heating value (HHV) and net thermal value or lower heating value (LHV) (McKendry 2001).

The HHV is the total energy, including the latent heat in water vapor, released when woody biomass is burnt. The LHV is the energy, excluding the latent heat in water vapor, released when woody biomass is burnt (McKendry 2001).

The thermal value of wood does not vary much between species (18.7-21.9 $GJ\cdot t^{-1}$) (Huhtinen 2005). In general coniferous species contain slightly higher thermal value than hardwood species as conifers contain higher lignin and resin contents than hardwood species.

The thermal value varies between tree components within a tree. The thermal value is slightly higher in bark, crown and stumps than in stem wood (Huhtinen 2005). Table 6 shows the thermal values of different tree components of some tree species.

Table 6: Thermal value ($GJ \cdot t^{-1}$) of tree components (Huhtinen 2005)

Tree species	Bark	Crown	Stem without bark	Whole stem	Full tree
Scots Pine	19.53	20.23	19.31	19.33	19.52
Norway spruce	18.80	19.77	19.05	19.02	19.29
Birch (*Betula spp*)	22.61	19.70	18.65	19.17	19.30
Grey alder	21.57	20.03	18.67	19.00	19.18
Trembling aspen	18.57	18.61	18.67	18.65	18.65

The thermal property of wood is one of the most important determining factors of wood quality as wood is one of the most complex materials whose properties depend on tree components, species, age, site conditions, and geographic location (Singh and Kostecky 1986; Macmillan 2001; Cassidy and Ashton 2007).

One study of Howard (1973) indicates that heating value ($MJ \cdot kg^{-1}$) does not correlate with geographic location, age of the tree and tree growth rate. Previous studies show that there is no correlation between heating value ($MJ \cdot kg^{-1}$) and stem diameter (Stringer and Carpenter 1986). Doat (1977) did not find any correlation between the heating value ($MJ \cdot kg^{-1}$) and the wood density (kg/cm^3). Wood heating value ($MJ \cdot kg^{-1}$) increases if the lignin and volatile contents of wood increase (Macmillan 2001).

Nurmi (1993; 1997) conducted research on the heating value of wood from different latitudes in Finland. The species are as follows: Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), downy birch (*Betula pubescens*), silver birch (*Betula pendula*), grey alder (*Alnus incana*), black alder (*Alnus glutinosa*) and trembling aspen (*Populus tremula*).

The studies show that in general when the latitude increases to the north the effective heating value of wood also increases (Nurmi 1993; Nurmi 1997). For example, for Scots pine (*Pinus sylvestris*) the wood from south latitude has effective heating value 19.97 $MJ \cdot kg^{-1}$, and the wood from north latitude has effective heating value 20.47 $MJ \cdot kg^{-1}$. Similarly the bark of Scots pine from south latitude has 20.67 $MJ \cdot kg^{-1}$, and the bark of the same species from north latitude has 21.63 $MJ \cdot kg^{-1}$. Bark and foliage have higher heating value ($MJ \cdot kg^{-1}$) than wood. The heating value ($MJ \cdot kg^{-1}$) in outer bark is higher than the heating value ($MJ \cdot kg^{-1}$) of inner bark.

Though the coniferous species, such as *Pinus sylvestries* and *Picea abies*, show the remarkable higher heating value ($MJ \cdot kg^{-1}$) in the wood from the north latitude comparing to the south latitude, the heat value difference is not always remarkable for hardwood species, such as *Betula pubescens*. For hardwood, even sometimes the wood from south latitude shows the higher heat value than the wood from north latitude. For example, for *Betula pubescens* the wood of branch of the tree from north latitude origin has higher effective heating value (19.08 $MJ \cdot kg^{-1}$) than the effective heat value (18.73 $MJ \cdot kg^{-1}$) wood of branch of the tree from south latitude origin. But for *Betula pubescens* the effective heating value (22.29 $MJ \cdot kg^{-1}$) of bark the tree from the south latitude is higher than the effective heating value (21.45 $MJ \cdot kg^{-1}$) bark of the tree from the north latitude origin.

Singh and Kostecky (1986) did one study on the heating values of different tree components of six softwoods and four hardwoods from Manitoba in Canada. They found the mean calorific values for the oven dry softwoods and hardwoods 20.15 $MJ \cdot kg^{-1}$ and 19.15 $MJ \cdot kg^{-1}$ respectively. They found the highest average calorific value in tree-top. When foliage is compared the average thermal value (20.98 $MJ \cdot kg^{-1}$) of softwood foliage is higher than the average thermal value (18.7 $MJ \cdot kg^{-1}$) of hardwood foliage (Singh and Kostecky 1986).

5. Biomass collection and storage

5.1. Collecting Woody Biomass

When bundling system of biomass harvesting is applied with the harvesting of primary forest products, such as sawlog and pulpwood, the FHR can be collected immediately after needle shedding. In this case FHR should be collected by creaming off the top of the FHR, and a certain percentage of FHR should be left in the forest to avoid contamination and to facilitate retaining nutrients in the forest (Bradley 2007; Alam *et al.* 2011). The bundles can be transferred to central terminal, pellet industry yard or biomass plant yard where the bundles can be stored and comminuted to prepare biomass feedstock.

Good time for collecting FHR of cut-to-length harvesting from the cut-over during dry season, especially late summer before starting cold season (Nurmi 2009). Woody biomass collection (chipping or grinding) from the open roadside slash piles should be conducted during dry season before snowfall (cold season).

If it is necessary to collect/harvest biomass from the forest during cold season covered slash piles can be used to procure woody biomass feedstock. Terminals which can be communicated throughout the year by using all season road network can be used to supply enough amount of biomass to the bioenergy plant (Bradley 2007). By comminuting covered bundled slash piles (which are already stored there) in terminal, pellet yard or bioenergy plant yard required amount of biomass feedstock for the bioenergy plants can be ensured during fall break, winter and spring break (Alam *et al.* 2009; Alam *et al.* 2011).

5.2. Woody Biomass Storage

After forest harvesting of primary forest products the FHR contains high moisture content and the moisture content in FHR decreases over time. In one study conducted by Nurmi (1999) shows that the initial moisture content of FHR is 56%. After leaving FHR for one year the moisture content becomes in cut-to-length harvested forest floor FHR 28.5 % and in the roadside slash piles the moisture content becomes 42.2 %. After one year the needle content of slash piles is 18.9% and the needle content in FHR in cut-over of cut-to-length harvested block is only 6.9%. Similar trends are observed in the study of Gautam (2010).

Gautam (2010) explored that after keeping one year in the field the moisture content of conifer residue is 20.6% in windrow pile and 25.3% in beehive pile respectively, and the moisture content of hardwood residue is 28.2% in windrow pile and 33.7% in beehive pile respectively (Figure 5). After keeping two years in the field the moisture content of conifer residue is 22.6% in windrow pile and 15.5% in beehive pile respectively, and the moisture content of hardwood residue is 19.9% in windrow pile and 28.9% in beehive pile respectively. Gautam (2010) also found the trends of decreasing ash content of FHR in cut-to-length harvested blocks over time. The

study shows that ash content of FHR in cut-to-length harvested blocks on dry basis after 1 year 3%, after 2 years 2.2%, and after 3 years 1.3% respectively.

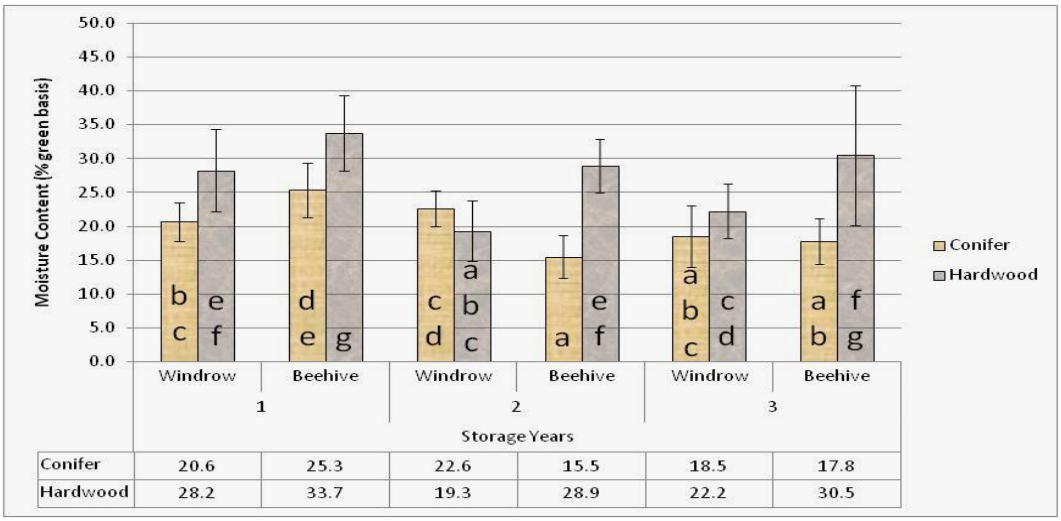

Figure 5: Moisture content of FHR in slash piles by keeping in the field for different years (Gautam 2010)

The nutrient concentration of leaves, twigs, and branches is very high. Nutrients are essential for the forest productivity. By leaving FHR in the field for certain time before collection it can be facilitated for leaving nutrients on site through leaching, mechanical mass-loss (shedding of foliage) and decomposition. Symonds *et al.* (2009) showed that after leaving FHR in the field the leaf mass left on site by black spruce 63%, by poplar 34% and by jack pine 29% respectively (Figure 6).

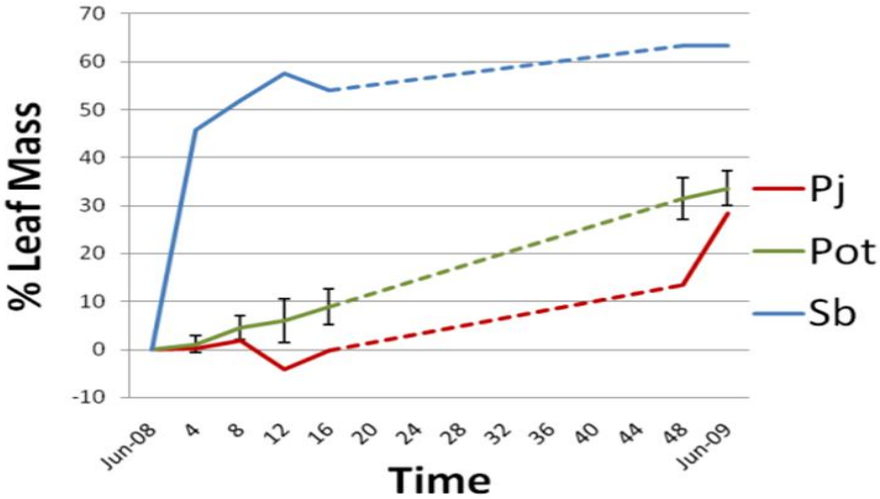

Figure 6: Leaf mass left on site in forest (Symonds *et al.* 2009)

To ensure the highest attainable biomass quality and also to retain the site productivity of the forest, FHR should be kept in bush at least one drying season. If slash pile is very large it can be harvested within 3 years. For the purposes of drying FHR, nutrient release to the site, silvicultural activities, successful natural regeneration, and to avoid wood decay the optimal time to keep FHR in the field is from 1-2 years (Alam *et al.* 2009; Alam *et al.* 2011).

Many factors play the role on the biofuel characteristics in the storage (Stahl *et al.* 2003; Erlich *et al.* 2006). In the first 6-12 months of storage of biofuel, the energy loss is 10-24 % and the matter loss 2-17 % (Rupar-Gadd 2006). The rate of energy loss depends on the location of biomass in the pile, while matter loss depends of the initial moisture content of the biomass (Koppejan 2007). When the biofuel particles are larger in size, temperature remains low and microbial activity is minimal. If the microbial activity starts the growth rate of microbial activity becomes faster (Jirjis 2005). If the biomass is stored under roof or covered, the loss of energy is only 5% over the storage period of 6-12 months (Rupar-Gadd 2006). More microbial growth and higher temperatures are associated with smaller sized biofuel particles (Jirjis 2005). Due to faster drying the larger sized wood chips minimize the microbial growth in the storage pile (Hakkila 1989; Pulkki 1991). Rupar-Gadd (2006) reported that the bulk density of biomass decreases with an increase in the size of the biomass particle. Temperature is the most limiting factor for microbial activity. At 0°C there is almost no microbial activity. Most fungal and bacterial activities cease at 60°C because the respiration of parenchyma stops at this temperature, although some bacteria can tolerate temperatures as high as 80°C. In smaller piles of biomass, temperature remains at the level of 60-70°C (Jirjis 2005; Rupar-Gadd 2006). Drying lowers microbial activity. When the moisture content is below 20% the microorganisms cannot use water because it is concentrated only in the cell walls. Larger sized particles dry out, but smaller sized particles trap moisture by forming

closed layers (Jirjis 2005; Rupar-Gadd 2006). Millar (2006) indicated that the heating value of woody biomass increases with a decrease in moisture content in storage.

Pile cover limits the access to oxygen and reduces microbial growth by forming closed layers and by restricting the movement of air in the pile (Hakkila 1989). The oxygen consumption of microorganisms in the pile of wood chips is only 1% in comparison with 21% oxygen consumption in fresh air. However, some bacteria can produce heat under anaerobic conditions (Rupar-Gadd 2006). Nitrogen plays an important role in the microbial activity. If bark and needle contents are high in the pile, the microbial activity is also high because of the high nitrogen content in bark and needles (Thörnqvist and Jirjis 1990). The level of biological and chemical activity in a biofuel pile can be indicated by the change in the concentrations of oxygen and carbon dioxide in the pile since microorganisms consume oxygen and emit carbon dioxide during their metabolic activities (Koppejan 2007; Rupar-Gadd 2006). Metals contaminate biomass piles. Metals accelerate the heating of biomass pile because biomass heat-generating reactions are catalyzed by metals (Kubler 1987; Thörnqvist 1987). Species type is an important component to be considered during biomass storage. For example, the overall heating value of birch is higher than the heating value of mixed conifer (Millar 2006).

Bundles can be stored long time in terminals or in mill yards before comminution. Chips should not be stored long time. To prevent microbial activity chips should be used as soon as possible after the materials are chipped to be used as biomass feedstock for power generation. Microbial activity in chips causes spontaneous combustion, emission of spore, and loss of energy. Generally, bundles do not show these hazardous problems. Bundles can be handled easily as these can be stored somewhat uniformly (Johansson *et al.* 2006). When ground biomass/chips are necessary to be stored these should be stored under cover and air circulation should be applied to keep the piles cool and dry (Bradley 2007; Alam *et al.* 2011).

6. Decision support system for woody biomass supply chain

There is no single method or system that is applicable to all situations (Pulkki 2003; Alam *et al.* 2009). Woody biomass supply chain can be managed in different ways depending on the situation. During woody biomass supply chain planning for energy production all phases of woody biomass procurement, from the sources of woody biomass to the ultimate consumers of energy, must be considered. A holistic approach is necessary for the planning of woody biomass procurement for energy (Sokhansanj and Fenton 2006; Sikanen *et al.* 2007; Wang 2007). It is essential to consider the biomass procurement and supply for the energy production as a vital part of forest sector supply chain (Alam *et al.* 2009; Alam *et al.* 2011). The decision support system (DSS) of bioenergy production from woody biomass feedstock is explored in English *et al.* (2000), Masera *et al.* (2006), Annevelink and de Mol (2007) and Sowlati (2009). The DSS of woody biomass supply chain should include many parameters including woody biomass harvesting, pre-processing, storage and woody biomass transportation (Alam *et al.* 2009).

Answers to the following questions are necessary for DSS of woody biomass supply chain (Annevelink and de Mol 2007):

- From what sources will the biofuels be collected?
- What types of pre-treatments are necessary and where are they needed?
- Where should the conversion plant be located?
- What is the best scale for the conversion plant?
- What are biomass procurement chain costs?
- What amount of energy will be consumed in this chain?

The following are some DSS for woody biomass supply chain (English *et al.* 2000; Masera *et al.* 2006; Annevelink and de Mol 2007; NRCan 2007; IEA Bioenergy 2007; FPInnovations 2011):

- Biomass logistic computer simulation (Biologics)
- Biomass logistic computer optimization (Bioloco)
- BIOmass-based Climate Change MITigation through Renewable Energy (BIOMITRE)
- Clean Energy Project Analysis (RETScreen)
- Wood Fuel Integrated Supply/Demand Mapping (WISDOM)
- The Wood Transportation and Resource Analysis System (WTRANS)
- Biomass Socio-Economic Multiplier (BIOSEM)
- BiOS (Biomass Opportunity and Supply)

7. Conclusions and recommendations

Canada can use its huge forest biomass reserves to maintain economically feasible and environmentally sound biomass supply chain for energy production in a sustainable way. Along this supply chains better communications between suppliers, customers and other actors are essential for the purpose of exploiting the best benefit from this chain. The transportation distance of biomass in Canada is greater in comparison with other biomass producing countries; therefore, the proper transportation system must be used to supply biomass for energy production in an efficient and effective way. The FHR chipping/grinding and the slash bundling are the two viable ways in the biomass supply chain for energy production in Canada. The costs of biomass supply chain can be reduced by integrating biomass harvesting with conventional forest harvesting. More or less every property of wood has the influence on biomass for the production of bioenergy by using biomass feedstock, and most of the wood properties are interrelated in influencing biomass utilization. Moisture content is the most important property of wood which determines the quality of woody biomass feedstock for energy production. By reducing moisture content in woody biomass the quality of woody biomass feedstock can be increased.

The following are the some recommendations to improve biomass supply chain for energy production:

- Whole biomass supply chain should be taken into consideration to optimize the supply of biomass for energy production.
- To minimize biomass transport cost moisture content of biomass should be decreased and bulk density of biomass should be increased.

- Innovation of the modern technology is essential to use biomass for the production of bioenergy in the most economical way.
- Research on different modes of transportation should be conducted for supplying biomass for energy production with minimum cost.
- Either same contractor needs to harvest main forest products and biomass from the same forest or there should be good coordination between the contractor of forest harvesting and the contractor of biomass harvesting to maintain the site quality of the forest, to procure good quality biomass, and to make the whole supply chain economically profitable and environmentally sound.
- Care should be taken not to contaminate FHR during harvesting of primary forest product, such as sawlog and pulpwoody.
- More research on biomass supply chain is essential to make the biomass supply chain for energy production more competitive.

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