LOGISTICS MODELING OF BIOMASS SUPPLY CHAIN IN ONTARIO

by

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ABSTRACT

The overall goal of this research is to investigate the logistics of agricultural biomass in Ontario, Canada using the Integrated Biomass Supply Analysis and Logistics Model (IBSAL). The applicability of IBSAL is demonstrated through simulating three case studies. Case A is for the supply of corn stover to Ontario Power Generation (OPG) in Lambton. Case B concerns the supply of baled switchgrass from three farms to a greenhouse operation. Case C is for the supply of straw or switchgrass bales from 5 growing regions to Mushroom Producers Coop Inc. (MPCI). For Case A, five scenarios of delivering corn stover to the OPG power plant in Lambton Ontario are investigated: (1) base scenario, (2) central storage scenario, (3) direct scenario, (4) barge scenario, (5) railroad scenario.

The net amount of annual biomass demand at the power plant is estimated to be 124,264 dry metric ton (Mg). For scenarios 1 to 5 the amount of biomass required to be harvested is respectively 160123, 155730, 151141,172480, and 170686 Mg per year. Also the total cost estimated to be respectively \$37/Mg, \$49/Mg, \$33/Mg, \$94/Mg, and \$81/Mg.

For Case B, the annual heating demand of a greenhouse located on southwestern Ontario near Lake Huron is calculated as 20,730 GJ/year. Roughly 2,200 Mg of switchgrass is required. Cost, energy consumption and carbon emission associated with the supply chain are \$66/Mg, 151.3 MJ/Mg and 10.4 kg CO_2/Mg, respectively. The dry matter loss is calculated to be 805 Mg. For Case C, the following scenarios are modeled: (1) Base case scenario, (2) Straw location scenario, (3) Straw field to MPCI, (4) Switchgrass location scenario. Delivery costs of the first scenario vary in the range of \$50-69/Mg. In the second scenario, the total average costs were \$74/Mg, \$68/Mg, and \$70/Mg for the storage on gravel, storage on gravel with pad and protected under shed. Scenario 3 showed how sorted and unsorted bales affect the cost. The forth scenario the average total costs were reported to be \$106.7/Mg, \$91.4/Mg, and \$90.8/Mg respectively for storage on the gravel pad on the gravel pad and protected under shed.

PREFACE

The literature review and the application of the IBSAL model of chapter 1 to chapter 5 are done by the major author (Hamid Khaleghi Hamedani) for the M.A.Sc. comprehensive exam. The initial model is developed by Professor Shahab Sokhansanj. Chapter 3 is published in a conference paper. Chapters 2 and 4 will be published in peer reviewed journals. The major supervisors, Professor Sokhansanj and Professor Lau, guided the author with their advice to do this project for Ontario Ministry of Agriculture and Rural Affair (OMAFRA).

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LIST OF SYMBOLS AND ABBREVIATIONS

A	total area of the greenhouse (m^2)
C	specific heat (kJ/kg ^oC)
C_1	fixed cost constant (\$/Mg)
C_2	variable cost constant (\$/Mg.km)
E_P	evaporation rate (mm/d)
F	fuel used for equipment (L)
H	height of each stack (m)
h	length of time to do the operation (h)
K	filling factor
L	distance (km)
n	number of equipment to get the operation done
N	number of air changes per hour
P	rated power (kW)
P_S	saturation vapor pressure (kPa)
P_V	vapor pressure (kPa)
T_i	inside temperature of the greenhouse (^oC)
T_o	outside temperature of the greenhouse (^oC)
u	air velocity (km/d)
U	overall heat transfer coefficient ($W/m^2.^oC$)
y	the number of year
CAF	capacity factor (%)
CHO	cost of harvest operation (\$/Mg)
COF	co firing (%)
CPA	cost of storage per area (\$/ m^2)
CPL	cost per load of transportation (\$)
EBC	extra biomass to compensate (Mg)
ED	energy demand (GJ)

GAS	gross area of storage (m^2)
GC	growing cost (\$/Mg)
GCA	generating capacity (GW)
HR	heat rate (GJ/GWhr)
IR	inflation rate
MBH	mass of biomass to harvest (Mg)
MOB	mass of each bale (Mg)
NAS	net area of storage under the bales (m^2)
NOL	number of loads
NOB	number of bales to be stacked
NOBT	number of bales per stack
OFC	old farm gate cost (\$)
RFC	recent farm gate cost (\$)
RH	running hour (hr)
TCS	total cost of storage (\$)
TDC	total delivered cost (\$)
TFC	total farm gate cost (\$)
TNC	transportation cost (\$/Mg^1)
TMD	total mass of delivered bale (Mg)
TTC	total transportation cost (\$)
TV	total volume of bales (m^3)
UDC	unit delivered cost (\$/Mg)

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I would also like to sincerely thank Jake Debruyn from Ontario Ministry of Agriculture and Rural affair (OMAFRA). Beside my supervisors, Jake was always a great help for me in collecting data from Ontario and validation the output of simulation. Also Ontario Ministry of Agriculture and Rural Affairs financially supported me in this project.

Dr. Mahmood Ebadian is not only a great friend but also a great leader. His encouragement and knowledge were always a bless in the last two years for me. I thank Leonard Ing from Ontario Power Generation (OPG) for helping me with the data of OPG. Also Don Nott, biomass grower in Ontario, helped me with farm data; and I really appreciate it.

Finally, working with brilliant researchers in Biomass and Bioenergy Research Group (BBRG) at University of British Columbia was my great honor. They provided a friendly environment for me grow and learn.

DEDICATION

I would like to dedicate this thesis to my family; my father, Hossein, who taught me how to conquer challenges in my life one after the other patiently; and to my mother, Zahra, who taught me love and forgiveness. Also I want to thank my sister, Atiyeh, and my brother in law, Amin, whose love and support was endless.

Chapter 1: Introduction

1.1 General

Ontario is the second largest province in Canada with an area of about 1 million km^2. The province stretches from 42° to 57° north latitude. Generally, three factors affect Ontario's climate: dry and cold air from the north, Pacific polar air from the west, and air from the south (Gulf of Mexico and the Atlantic Ocean). Polar air causes Northern Ontario to be cold, whereas Atlantic and Gulf air causes Southern Ontario to be relatively warm. Webber and Hoffman (1970) classified Ontario climate as humid continental. Hudson Bay, the Great Lakes, James Bay, and Kirkland Lake, moderate the weather in Ontario. The areas which are closer to a lake have a larger number of growing-degree-days.

Ontario has almost half of Canada's Class 1 agricultural land (George et al., 2002), which totals about 3.6 million hectares, and the average farm size is 94 hectares. Hay, soybeans, grain corn, and winter wheat are the most important field crops in Ontario, as shown in Table 1.1. These crops are planted on some 90% of the agricultural land area (Oo et al., 2012 a). Other field crops are spring wheat, canola, barley, fodder corn, beans, oats, rye, tobacco, and mixed grain.

1.2 Agricultural Biomass in Ontario

The main sources of agricultural biomass in Ontario include: 1) grains such as corn, soybean, cereals, beans, and canola; 2) forages such as annual and perennial, grasses and legumes, hay crops, and new grass crops 3) crop residues such as corn stover, corn cobs, soybean stubble, and cereal straw; 4) by-products such as food processing residues; and 5) manure. There are also non-agricultural sources, for instance, biosolids from wastewater treatment and construction wastes (McDonald 2010).

The end-users of biomass require biomass for diverse purposes. Some of the most important uses are for bedding in the mushroom industry, vegetable mulch and heating. Each of the end-users has own specifications about the size, mineral and moisture contents, and ash content.

Approximately 7 million DMg (DMg is defined as Dry Mg or tonne, based on dry matter) of corn stover is produced in Eastern Canada (Savoie et al., 2004). The Biomass Inventory Mapping and Analysis Tool (BIMAT) may be used to show the availability of the corn stover in the Ontario region; for instance, the four regions of Chatham in Southern Ontario.
The amount of wheat straw available in the four regions of Chatham has also been reported. The minimum and maximum amounts of wheat straw were 222,000 DMg (2007) and 474,000 DMg (2008), respectively, with an average of 363,000 DMg (Duffy and Marchand 2013). Wheat straw and corn stover are compared in Table 1.2.

Switchgrass (*Panicum Virgatum*) is a warm season perennial grass. It is drought tolerant, and adaptable to the low nutrients (semi-arid) soil (Sokhansanj et al. 2009, Sanderson et al., 2008). As a native crop in North America, it is also resistant to pests. More than 200 ha of switchgrass are grown in Ontario, primarily for use as animal bedding, mushroom bedding and fuel for heating. Switchgrass is seeded in the range of 6.8-9 kg/ha in spring. During the first year of establishment, switchgrass cannot be harvested. Nott Farms in Clinton, Ontario solved this problem by co-seeding spring wheat and switchgrass, so that income can be derived from growing spring wheat. Switchgrass is harvestable with a yield reaching 7.5-15 Mg/ha 3 years after the cultivation and then constant yield 15-20 years after establishment (Oo, et al. 2012 a). The establishment cost of switchgrass is $875-1125/ha. Growing switchgrass is more beneficial in comparison to miscanthus as it can be easily grown from seed and requires less investment. Switchgrass can be considered as a bioenergy feedstock in North America (Samson et al. 1992) as it has the following advantages: high productivity, moisture efficiency, low major nutrients (NPK) requirements, low harvest costs, farmer friendly and eco-friendly. Hengeveld (1989) and Turhollow and Perlack (1991) compared the relative CO_2 emissions per unit of energy which is shown in Table 1.3.

Miscanthus is an herbaceous perennial grass with a yield of 15-30 Mg/ha in Ontario. Once it is established it can be harvested for 10-15 years. Water and nutrition requirements of miscanthus are relatively low. In Ontario, more than 200 ha of agricultural land grows miscanthus, with an average yield of 18.75 Mg/ha (Oo, et al. 2012 a). To grow miscanthus, rhizomes or plugs are planted initially (at 15000 rhizomes or plants/ha in Ontario) since miscanthus has no seeds. It is vital to select a variety of miscanthus that is able to stand the severe winter in Ontario especially in the first year. After the second year it can be harvested.

The harvest schedule is in the spring after the leaves are lost in the winter. Four years after planting miscanthus will achieve the highest yield. Following this sequence, the nutrients will go back to the soil leaving the harvested miscanthus on the ground during the winter, while letting the useless nutrients to be removed. This would make the biomass more desirable for the combustion process (Oo, et al. 2012 a).

Willow and hybrid poplar are classified as fast-growing, high yield woody biomass. They have a short rotation of 3-5 years. Usually a high density system having 15,000-20,000 stems/ha is designed to grow these crops. The annual yield is 6-10 Mg/ha in Canada. Purpose-grown woody crops may be utilized for making pellets, electricity and heat, biofuels, and newly developing products. The common species across most of Ontario are Shrub Willow and Shining Willow, whereas Slender Willow and Peachleaf Willow are found in Southern Ontario (Grillmayer, 2009). Some of the species of poplar which are native to North America include *P. balsamifera, P. trichocarpa and P. laurifolia* (Derbowka et al. 2012).

The results of a study conducted by Kludze et al. (2010) suggested that biomass may be more sustainably supplied (and in greater potential quantity) by dedicated deep rooted biomass crops rather than from crop residue removal. The actual amount of supply for these dedicated biomass crops depends on factors including production costs, yields, opportunity costs of production and the price that purchasers are willing to pay.

1.3 Feedstock Logistics and Existing Models

Feedstock logistics is defined by the following operations: harvest, storage, and transport. The objective is to deliver a specified quantity and quality of feedstock to the biorefinery at a competitive price. Failure in any of these delivery requirements would decrease the profitability of the biorefinery (Sokhansanj et al. 2009). Post harvest processes contribute greatly to the cost and quality of feedstocks. For example, size reduction, drying, and densification (pelletization) operations transform the bulky raw biomass to a well-defined feedstock with a predictable performance. Pelletized biomass can be transported and stored efficiently in the existing well-developed grain handling infrastructure.

Often the biomass supply chain is analyzed with a powerful model in order to fully control the variables and constraints of the scenario. A number of models have been developed to synthesize the biomass production system. Hwang (2007) simulated the soil moisture content, weather condition, and the supply chain of biomass production systems. In the model the different scenarios are checked based on the working days. The number of working days was found to inversely affect the cost of different scenarios.

Noon and Daly (1996) developed a computer- based decision support system, called BRAVO (Biomass Resource Assessment Version One). This model was used to simulate the delivery of woody biomass to 12 coal-fired power plants in Tennessee. To predict the transportation cost precisely, a GIS platform is used in this model. Nilsson et al. (1999) developed the SHAM (Straw Handling Model) to investigate the delivery options. SHAM is well developed to simulate the harvesting seasons. It is helpful in comparing management strategies and machinery supply chains. Graham et al. (2000) developed a model based on Geographic Information System (GIS). The model is used to assess the cost of switchgrass in eleven states in the US. Graham compared the transportation costs and facility demand in different states. For a facility with a demand of 100,000 Mg/year the cost reported ranges from \$33 to \$58/DMg. Resop et al. (2011) used Raster based GIS method to model switchgrass production. In that study, the objective was to find the location of satellite storage sites (SSLs). The Gretna and Keysville regions in Virginia were considered as case studies. The outputs showed the radius of switchgrass production required to meet the demand of a fictitious power plant.

1.3.1 IBSAL Model

Sokhansanj et al. (2006) developed a framework for modeling and simulating the biomass supply chain logistics from the field to the biorefinery at US DOE’s Oak Ridge National Laboratory (ORNL) and the University of British Columbia (UBC). It was the first version of the Integrated Biomass Supply Analysis and Logistics model (IBSAL), based on forage crop harvest and transport unit operations. Initially, the framework has been used as a tool to assess the collection, transport and storage of crop residues (corn stover and wheat straw). Sokhansanj et al. (2008) further described the sources of data and relationships used in the functional elements of IBSAL, addressing the various issues (expected yield, moisture changes, dry matter loss, etc.).

The IBSAL model comprises of three components: The Excel file, the simulation model and the optimization model. The Excel file includes all the required worksheets to enter the input data and record the outputs from the simulation and optimization models. The model is written in ExtendSim v.8 (www.ExtendSim.com), which consists of a network of operational modules threaded into a complete supply system.

Main features of the IBSAL model:

1. It consists of a network of independent operational modules which can be threaded into a complete supply system, and each module contains mathematical equations to describe a process or event
2. As a dynamic model, IBSAL uses weather data and calculates biomass moisture content and traces dry matter recovery throughout the supply chain operations;
3. The model can incorporate multiple feedstocks (all of the biomass types) available in the supply area for bioenergy production;
4. The number and location of depot storage sites are prescribed by the model based on the locations of the bioenergy plant, biomass producers and the amount of biomass flowing in the supply chain. In addition, the capacity of each depot location is estimated by the IBSAL model; and
5. The model can look after "demand management" by enabling the feedstock managers to schedule the operations in the supply chain to meet the biomass demand for the bioenergy plant. The biomass demand could be hourly, daily, weekly, monthly or annual.

The process modules are drying, wetting, and dry matter loss. The events are operations such as baling, loading, transporting, stacking, grinding, and storing. Biomass flows from one module to the next through a connector. To date, 46 modules/functional elements have been developed. Additional modules to extend the capabilities of IBSAL to simulate advanced harvesting operations and new biomass feedstocks have yet to be developed. The need for IBSAL to be expanded to include the harvest, storage and transport requirements of high-productivity biomass/energy crops in humid regions (Ontario) and hence higher-moisture biomass has been recognized by ONRL personnel. The model can also be extended to evaluate preprocessing options such as drying (natural and artificial), biomass densification in large packages or in granulated forms (pellets, cubes, briquettes).

The IBSAL model has undergone several improvements over time. A new version of the simulation model IBSAL–MC, was developed for multiple agricultural biomass (Ebadian et al., 2011). This model was based on the IBSAL model and was used for simulating the supply of wheat straw to a cellulosic ethanol plant in Prince Albert, Saskatchewan.

Inputs to the IBSAL model

The input data set of IBSAL model consists of five categories as shown in Figure 1.1:

1) Initial data set which consists of the crop type, standard grain moisture content for estimating biomass-to-grain ratio, average grain yield (Mg/ha), average biomass yield (DMg/ha), yield to be deducted for conservation (DMg/ha), annual mass demand (DMg), total crop supply area (ha), number of items simulated, mass per item (Mg), and area per item (ha);
2) The schedule data set that consists of week number, percentage of harvest, and moisture content at harvest time;
3) The weather database that consists of day, temperature, relative humidity, evaporation, and precipitation;
4) The cost database that consists of interest rate, wage rate ($/hr), benefits rate, fuel cost ($/L), fuel tax ($/L), truck speed (km/hr), and machinery cost ($/hr);
5) Equipment data that consist of transporters, loaders, processors, handlers, tractors, and harvesters.

The IBSAL model uses the inputs and does the calculations when the user runs the simulation. The modeling environment is written in both discrete and continuous simulation. This dual capability is very important because the queuing and servicing aspects of the logistics model require a discrete analysis while the moisture absorption processes and quality attributes require a continuous modeling program. ExtendSim simulation has different desirable capabilities as it can be used for both discrete and continuous simulation purposes.

Outputs from the IBSAL model

The outputs consist of the cost ($/Mg), energy consumption (MJ/Mg), carbon emission (kg CO_2/Mg), recovered biomass (Mg), dry matter loss, the number of machinery and the number of days required to finish the operation (Figure 1.1).

The IBSAL model provides the distribution of logistics costs based on variations in the input parameters such as biomass yield, weather conditions, harvest schedule, and moisture content. The cost distribution can be used to delineate the worst case scenario and the best case scenario -in the supply chain in terms of logistics costs. Moreover, the range of logistics costs can be estimated with a specific confidence interval. The impacts of the input parameters on the performance of the supply chain are assessed by the IBSAL model. For example, the effect of changes in the biomass yield on the total biomass delivery cost is ascertained by the IBSAL model.

The number of machines required, their utilization rates, and their daily schedule are generated by the IBSAL model. The model determines the amount of processed biomass in each operation and the associated recovered biomass and dry matter losses. The IBSAL model also estimates the amount of energy input required to run the equipment in the supply chain and their associated emitted CO_2. These outputs can be used in a life cycle analysis to evaluate the environmental impact of the bioenergy plant on the local communities.

1.4 Scope and Objectives of the Study

The development of a viable cellulosic bioenergy industry requires the integration of feedstock supply system with biomass production at one end and with biomass conversion at the other end.

This study is focused on the feedstock harvest, post-harvest processing and storage logistics component of a bioenergy project. The anticipated deliverables for this project will be an analytical tool for analyzing and optimizing suites of equipment and strategies for harvesting and pre-transport processing of plant materials for “Just-In-Time” delivery of biomass to biorefinery (conversion processes). This will provide an integrated biomass production, logistics, and bioconversion management system that can be used by bioenergy facilities planners, biomass producers, and bioenergy plant operators to optimize seasonal feedstock production and delivery.

Our goal is to evaluate and define the equipment and infrastructure options for collection and handling of agricultural biomass materials in Ontario, Canada. The biomass supply logistics are characterized by large collection areas, time- and weather- sensitive crop maturity, a short window for biomass collection, and competition from concurrent harvest operations. An optimized collection, storage and transport network would ensure timely supply of the biomass at minimum costs.

The IBSAL model was used in this study for simulation and applied to agricultural biomass. Three cases in Ontario were investigated, and they were classified on the basis of end-users. Case study #1 is focused on OPG "Ontario Power Generation" (corn stover as biomass for power production). Case study #2 concerns the greenhouse industry (switchgrass combusted in a furnace to provide heat). Case study #3 involves the delivery of switchgrass to a mushroom facility to be used as bedding.

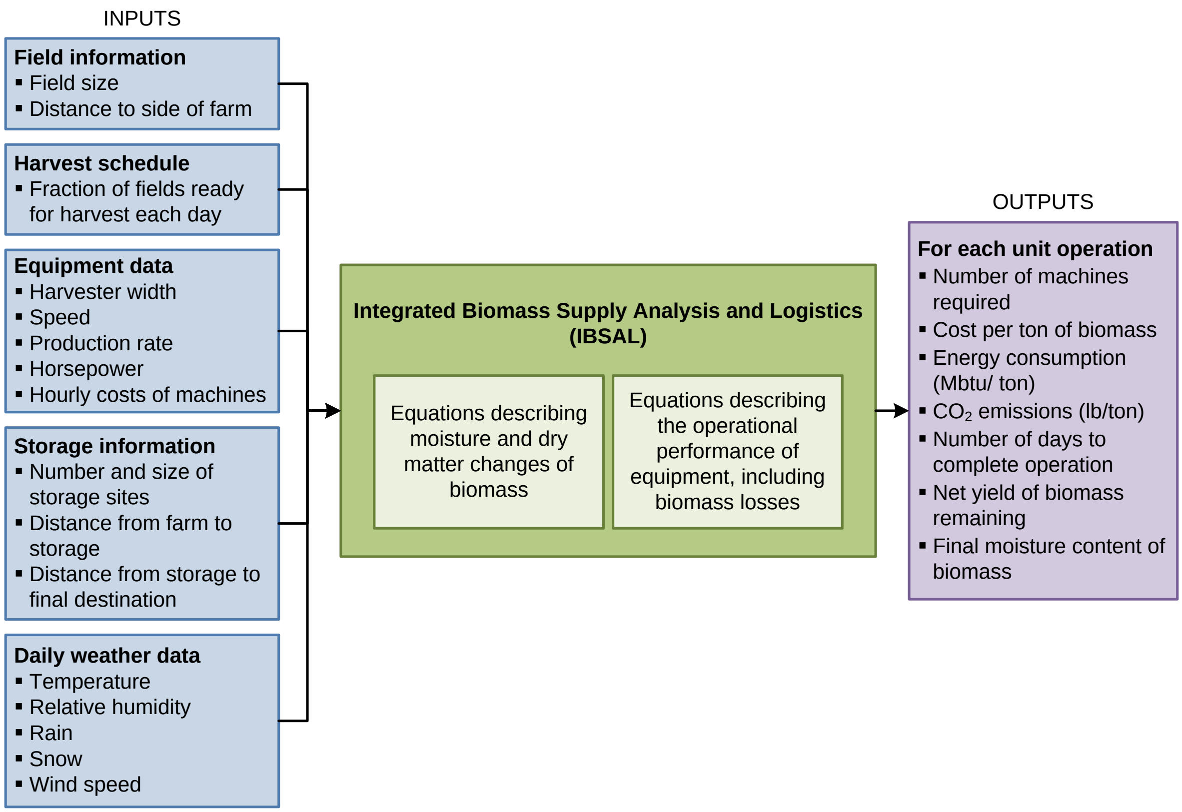

Figure 1-1 Schematic Diagram of the Experimental Procedures of Supply Chain of Biomass (Sokhansanj et al. 2008)

Table 1-1 Major crops grown in Ontario (Oo et al. 2012 a)

	Hay	Soybeans	Grain corn	Winter wheat	Other field crops
Percentage	29	27	22	11	11
Million hectares	2.47	2.32	1.86	0.93	0.95

Table 1-2 Comparing wheat straw with corn stover (Duffy and Marchand 2013)

Wheat straw	Corn stover
Several chances of baling	Harvest in the fall with unpredictable weather / Rush to complete before winter
Moisture content is not problematic	Lower moisture content is more desirable for longer storage
Allow much wider window for baling	Time spent on removing the moisture content causes a lack of time for baling

Table 1-3 CO_2 emission per unit of energy content for various energy sources

Energy Source	kg CO_2/GJ energy
Oil sands	30.0
Coal	247
Petroleum	22.3
Natural gas	13.8
Switchgrass	1.90

Chapter 2: Delivery of Corn Stover to Ontario Power Generation (OPG) in Lambton, Ontario, Logistics, Cost Analysis and Dry Matter Loss

2.1 Overview of Logistics and Availability of Corn Stover

The logistics of corn stover delivery include harvesting, collection, densifying, storage and transportation.

2.1.1 Harvesting, Collection and Densifying Corn Stover

Corn stover is one of the agricultural biomass, for which scientists have shown to be of practical use as a source of energy (Leask & Daynard, 1973; Al-Kaisi & Hanna, 2002), for instance, in power plants. The heating value of the corn stover, at 35% wet mass basis, is reported 17.8 GJ/t or GJ/Mg (Boundy et al. 2011).

Hereinafter, the units “t (tonnes)” and “Mg (10^3 kg)” will be used interchangeably. Increasing corn yields, particularly over the last decade, have increased the amount of stover remaining after the grain is harvested. Therefore, it is important to know the corn yields over time. In Ontario, corn (*Zea mays L.*) yield has increased by two-folds from 76 bu/ac in the 1960’s to 156 bu/ac (4 t/ha to 10 t/ha) in 2012 (Duffy and Marchand 2013). The production of grain corn and stover are closely related and are often assumed to be in 1:1 ratio by mass (dry matter basis) (Glassner et al., 1999; Petrolia, 2008; Morey et al., 2010).

McDonald (2010) provided estimates of dry matter yield being 3.96 t/ac and 3.10 t/ac for corn yield and corn residue yield, respectively. They suggested that 50% should be trimmed from the value for practically available corn residue; however, sustainably available corn residue remained a subject of future work. Oo (2010) reported that the recommended residue harvest would be 1.26 t/ac or 3.2 Mg/ha if soybeans-winter wheat-corn rotation is practiced. Duffy and Marchand (2013) have summarized the advantages and disadvantages of removing the excess corn stover from the field as suggested by researchers such as (Glassner et al. 1999, Al-Kaisi and Hanna 2002, Oo and Lalonde 2012b). They made some assumptions in the financial analysis pertinent to the development of a business case for a cornstalks to bioprocessing venture. The assumptions included grain corn yield of 10.5 t/ha and stover moisture content of 35% (wet basis). Moreover, they assumed stover removal rate of 30%, taking sustainable availability into consideration. With these assumptions, the estimated amount of stover removed (harvested) equals 2.2 t/ha (dry matter basis). Hence, depending on the cultivation practice, the sustainably available corn stover can range from 2.2-3.2 Mg/ha.

Harvesting

The common harvest method for corn grain is by using the combine. Stalks are chopped, and chopped stover is raked to make it easier to be baled. The suite of machinery previously used for forage harvesting can be used for corn, hay and straw. Fall is considered as the usual harvesting season for the corn stover in Ontario. Depending on the hours of baling and days of harvest, the moisture content at harvest time could vary from 14 to 33% (Sokhansnaj et al. 2002).

Raking and baling

To make baling easier and more efficient it is necessary to have stover in a row. Rakes have vertical rotary tines that put the cut crop in a row. Using rakes will also cause the crop to lose moisture content. The crop is baled using round baler or square baler. It is recommended to switch from round baler to square baler that can make bales with higher density. The transportation and storage of square bales are more efficient (Oo et al., 2012c). Round bales can deform in shape during storage, making it tougher to transport the bales.

Swathing and baling

There is an option of using swather instead of using combine, chopper and rake. This equipment cuts and windrows the crop to make it ready to be picked up by other machinery such as baler (Twidale et al. 1972). Swather can be self-propelled or pull type.

Mowing and chopping

Forage harvesters can be self-propelled or pull type. They chop and blow the silage to either a truck moving beside the harvester or a wagon attached to the harvester. When the wagon is filled, it is moved to the storage. Another wagon is then hitched to the harvester.

2.1.2 Storage and Transportation Systems in Ontario

Storage

After harvesting the biomass, farmers put the bales on the side of their farms before transporting to the storage. Usually to keep corn silage and hay from deterioration they are covered with a tarp or each bale can be wrapped with a plastic film. Biomass can be ensiled in upright silo, concrete bunker, and plastic ag-bag. Biomass will be fermented slightly and this prevents the biomass from further degradation. For the chopped biomass there is another option of piling biomass in the farm. The top layer will be harder and keep the rest of the biomass from rain and snow. However, this option makes it more probable to lose biomass due to spoilage.

The options for storing biomass in Ontario are: unwrapped bales under tarp, unwrapped bales in enclosed structure, wrapped bales stored outside, chopped biomass in enclosed structure, chopped biomass in vertical silo or bunker, chopped biomass in field piles. While the storage capacity is 300-500 Mg, the method of unwrapped bales under tarp is one of the cheapest methods which costs 5-8 ($/DMg). The most expensive method is chopped biomass in coverall which costs 32-38 ($/DMg) (Oo et al., 2012c). Note that the unit "*DMg*" is hereby defined as "1 Mg of the dry matter".

There is no significant difference in the dry matter loss of round bales versus square bales in storage. Dry matter loss of round and square bales amounted to 17-38% for outdoor storage and 2-5% for indoor storage, depending on the initial moisture content (Shinners, et al., 2007).

Transportation

As the density of biomass is lower in comparison to other goods, the biomass load weight is usually less than the truck weight limit. Energy input to the baler is one of the limitations in making high density bales. The normal density of bale is 161 kg/m^3 whereas high density of bale is 177 kg/ m^3.

Transportation of biomass comprises of on-farm transportation and transportation to the end user. On-farm transportation can be done by both loader and the bale accumulator. Transportation to the end user can be done by: farm tractor and wagon, transport truck, marine, or rail (Sokhansanj et al., 2009). The most common type of transportation is transport truck. A wheeled loader telehandler/overhead crane system is used to load and unload the bales. Other options for unloading the bales include unloading from truck using a self-powered, live bottom (walking) floor, floor trail or dumped off using a regular dump trailer or a trailer tripper. It is easier to have biomass baled, as it makes the identification and tracking system easier. In the conversion process, bale grinder or chipper can be used.

In the supply of biomass to OPG, there is an option of delivering biomass through shipping in Lake Huron. Lake Huron is a part of The Great Lakes Marine Transportation System (GLMTS). GLMTS consists of the other great lakes (Lakes Ontario, Erie, Michigan, and Superior), their connecting waters, and the St. Lawrence River. GLMTS is considered as one of the largest fresh water transportation systems on earth (Stewart, 2006).

The 145 km St. Clair River flows from Lake Huron towards Lake Erie. Cargoes pass through St. Clair River to deliver biomass to OPG. During winter, ice in the St. Clair River is at such a depth that ice breakers might not work. During 2004 the seaway was used for forty weeks in winter, which was the longest time ever recorded. Shipping materials is feasible during nine months; however, there should be another option for transportation in the winter season (Higginson et al., 2007). According to the St. Clair Navigation Safety Regulations, it is prohibited for ships with a length of 20 m or longer to have a speed that exceeds 19.2 km/h. There is not a specific weight restriction in shipping and products can be carried based on the deadweight tonnage of the ships.

Square baler is used in the harvest section of this scenario, as it is easier to transport square bales. Also, it is obvious that less bulky biomass has lower transportation cost. The location of storage affects the cost of transportation. Fixed and variable costs of shipping are \$19.6/DMg and \$ 0.0133/DMg/km respectively (Flynn, 2007; Samson, 2008; Sokhansanj and Fenton, 2006; Sorensen, 2005). The specifications of the barge are listed in Table 2.1.

The length of track for freight and passenger transportation is 18,982 km in Ontario (Stat Canada, 2009). This is the longest track in Canada. In this study it is assumed that the locomotive is pulling 100 box cars at a speed of 90 km/h. Box cars are usually used in transporting some products that need in-transit protection. They are suitable for carrying wood pulp, panel product, metals, coal, and agricultural products. Usually 15.2 and 18.2 m box cars are used for the above mentioned goods. Moreover, it is assumed that 18.2 m double-door box cars with the dimensions 3.3 m x 18.5 m x 2.9 m are utilized. To carry larger products it is desirable to use the double-door type box cars. The cost of rail transportation encompasses variable costs and fixed costs, which are assumed to be 0.0277 \$/DMg/km and 17.1 \$/DMg, respectively (Oo, 2012 c).

2.2 OPG Power Plants, Issues, Principles and Goals

This study provides the background for investigating the logistics of moving agricultural biomass to an existing coal-fired power plant in Ontario. Ontario Power Generation (OPG) supplies the electricity for the province of Ontario in Canada. Recently, the Government of Ontario supported OPG to be more involved in environmentally friendly projects in their current coal-fired power plants by substituting biomass for coal. One of the challenges of this substitution is the steady supply of low-cost biomass to the power plants throughout the year. Both the challenges and solutions of supplying materials to one of the coal-fired power plants of OPG are discussed.

OPG runs different stations to generate electricity, including: three nuclear power stations, five thermal power stations, 65 hydroelectric power stations and two wind power turbines. OPG has the capacity to produce more than 19,000 MW power. Nuclear and hydroelectric provide approximately 95% of the total power generation by OPG (OPG annual report. 2012). The five thermal power generating stations of OPG are: Atikokan, Nanticoke, Lambton, Thunder Bay, and Lennox plants. These stations have the capacity of 211 MW, 1880 MW, 950 MW, 306 MW, and 2100 MW, respectively. With exception to the Lennox Generating

Station (GS) which uses both oil and natural gas, all of the other stations utilize coal to generate thermal energy (Ontario Power Generation. 2013).

The focus of this survey is the Lambton GS and it is specified with red circle in Figure 2.1. The Lambton GS is located on the St. Clair River, in St. Clair Township 26 km south of Sarnia, Ontario. There are 300 people working in the plant. OPG uses Lambton GS to support the other stations in the periods of peak demand and increase the reliability of the system. Removing the coal-fired power plants can pave the way to reduce the carbon footprint of energy generation. One of the main issues of generating electricity by firing coal is the emission of the greenhouse gas (fossil-fuel based carbon dioxide). There are regulations which are approved by the government in this regard such as Regulations of Reduction of Carbon Dioxide from Coal-fired Generation of Electricity in 2012, and another regulation which will be started on July 1, 2015.

Based on these regulations the maximum carbon dioxide emission can be 420 Mg CO_2/GWh for coal-burning units, raising a new challenge for OPG. Currently, Nanticoke and Thunder Bay coal-fired power productions in Ontario emit respectively 1014 and 1166 Mg CO_2/GWh (Ozis et al. 2007). To meet this challenge, OPG is investigating to shut down coal-fired power plants of Lambton and convert them into co-firing biomass and natural gas. Converting existing coal-fired units to biomass energy is one way to address the CO_2/GWh emissions limit. This scheme would have the following advantages for the environment, OPG, and people in Ontario:

1. Reducing the carbon footprint as the main goal of this achievement.
2. OPG has already taken some steps to protect the environment by doing other projects and having various certificates. Some of the OPG`s recognitions include: being internationally authenticated to the ISO 14001 Environmental Management standard and being selected in North America as one of the cleanest coal-fueled units due to the minimum emission of sulfur dioxide, nitrogen oxides, and mercury. Therefore, the biomass substitution is following the previous efforts of OPG toward caring for the environment. (Ontario Power Generation. 2011)
3. This project needs hundreds of thousands tons of biomass in pellet form whether from agricultural by-products or wood. It will be a great opportunity for developing new markets in different sections of the agriculture and forestry industries. Therefore, in each

of the processes from the source of biomass to the gate of OPG, many people and industries will be involved. (Mitchell et al. 2010)

4. Using the existing facilities can prevent a retrofit. Zero cost may be achieved by just converting the type of fuel and keeping the facilities.
5. It can be used as a sustainable alternative to support other generating stations of OPG.

One of the potential options in the biomass conversion project of OPG is the Lambton GS. This station requires pellet volume of 375,000 ODMG (oven dried metric tonnes)/year which is 19% of the total pellets needed for OPG. Three pellet plants are required to meet the demand of Lambton GS (Kennedy et al. 2011). According to statistics compiled by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), in the western region of Ontario where the Lambton GS is located, 748,878 ha of farmlands are under cultivation of different crops and total land for energy crops is 244,107 ha.

Reducing the biomass delivery cost is one of the critical goals in all of the projects. Energy crops such as switchgrass, Miscanthus, and willow are presently available in Ontario. From the logistic point of view, the supply of agricultural biomass to the OPG generating station has to be optimized in order to make the biomass a commercially viable fuel. In this regard, the entire supply chain from the biomass sources (farmlands) to the gate of the power plant will be modeled and evaluated in order to find solutions to improve the biomass delivery schedule and the associated costs.

2.3 Methodology, Application of the IBSAL Model to the OPG Biomass Fired Projects

The modeling and simulation results of five supply chain scenarios which concern the delivery of corn stover to OPG are presented in this chapter. These scenarios are: 1) base case scenario; 2) central storage scenario; 3) direct scenario; 4) barge scenario; and 5) railroad scenario, as shown in Figure 2.2. The reason for having five scenarios is to compare the options of transportation. However, in the process of making comparisons, the feasibility of having central storage, side-of-farm storage and using round baler or square baler are also investigated. Inputs to the model include grain yield, proportion of the cultivated land under the biomass crop, grain harvest dates and the progress of harvest operations. Daily weather data including average temperature, relative humidity and precipitation for each collection area were also inputs to the model. The model outputs are the cost of operation, percent biomass recovery (subtracting biomass loss in the field), energy consumption, carbon emission, number of required machinery, and bottlenecks in the collection and transport operations.

The first set of operations in the supply chain is the harvesting and collection of biomass, in which biomass is removed from fields and transported to the nearby storage sites. These operations include cutting, in-field drying, and biomass collection, densifying and transport to storage. Harvested biomass can be prepackaged and kept on the farm, kept on the roadside storage or transported to larger satellite storage (depot) located between the farms and the bioenergy production plant. While in depot the biomass may be processed into a form with greater mass and energy density. The handling and transport operations include loading biomass onto the vehicles for shipping to the plant. The idea is to prepare feedstock in a form that can be directly used in the conversion facility without much more pretreatments.

The IBSAL model was modified based on the specifics of the Lambton power plant. In order to control the bottlenecks in the logistics of biomass in Ontario, modeling and analyzing the whole process is recommended. In this respect, The Pembina Institute did some research for OPG to compare the effect of natural gas and biomass on the periodic changes of atmosphere, with the main focus on the life cycle emission of the wood pellet industry (The Pembina Institute 2011). The model of Pembina did not evaluate the ongoing forestry practices in Ontario, but it concentrated on the wood pellet industry. Researchers from the University of Toronto have evaluated the life cycle of carbon emission pertinent to biomass fuel (Spatari et al. 2005). OMAFRA (2013) and Ontario Power Generation (2012) have also evaluated the possibility of using agricultural biomass in industries and reducing the carbon footprint.

Depending on the biomass availability in a region and the biomass demand, a portion of available biomass may be required to meet the demand. In such cases, the IBSAL model determines the farms needed to be contracted. The selection of farms is based on their locations, the amount of biomass they produce and their distances from the bioenergy plant. Different scenarios can be developed and compared in the IBSAL model. The most efficient scenario can be selected based on different measures such as logistics costs, dry matter loss and emitted CO_2 where applicable. Examples of these scenarios can include square baling and chopping.

Figure 2.3 shows the simulation of the biomass supply chain from harvest to the end user. The most cost-effective scenario can be obtained by determining the minimum (supply) radius to meet the biomass demand by the OPG power plant. Although the costs of harvesting, baling, transportation and storage can be roughly estimated, the IBSAL model can estimate these costs in a better way based on the dynamics and uncertainties in the supply system such as dry matter loss, machine breakdown and weather conditions. In addition, the optimal number and location of the storage sites can be determined by the IBSAL model.

The five scenarios involving different collection and transport systems for corn stover were then assembled and analyzed. More details about each scenario are shown in Figures 2.4-2.8.

Scenario 1 – Base case scenario

Harvest grain, shred crop residue, bale biomass (round baler), transport bales to the field edge and stack, load bales on truck and transport to biorefinery, unload the bales in the storage of the biorefinery (Figure 2.4). The base case scenario is a typical logistics system.

Scenario 2 – Central storage scenario

Harvest grain, shred crop residue, bale biomass (round baler), 'load and on-farm transport' as well as 'unload on the side of the farm by stacker stinger (auto-collector)', load the trucks, transport to the central storage, unload the bales in the central storage, load the bales onto trucks, transport to biorefinery, and finally unload into the storage at the biorefinery (Figure 2.5).

Scenario 3 – Direct scenario

Harvest grain, shred crop residue, bale biomass (square baler), with the arrival of the truck to the farm, load the bales and transport directly to OPG, and then unload the bales into the OPG storage (Figure 2.6).

Scenario 4– Barge scenario

Harvest grain, shred crop residue, bale biomass (square baler), load flatbed truck, move the bales to the side of the farm, unload the bales and stack them, load the truck, transport to water front, unload trucks, load the barge, transport through Lake Huron, unload the barge, load the truck, transport to OPG, unload and stack the bales into the OPG storage (Figure 2.7).

Scenario 5– Railroad scenario

Harvest grain, shred crop residue, bale biomass (square baler), load flatbed truck, move the bales to the side of the farm, unload the bales and stack them, load the truck, transport to train station, unload the trucks, load the boxcar, send the train to OPG, unload the boxcar, load the truck, transport the bales to OPG, unload the truck and stack bales into the OPG storage (Figure 2.8).

2.3.1 Input Data and Assumptions

The IBSAL model requires input of biomass quantities, biomass yield, geographical distribution of the supply area, moisture contents, typical dates for start of harvest, length of time for harvest and climate data.

Table 2.2 lists the input data required to perform the analysis. Climate data are available from Environment Canada Data Centre. This study used the Centre’s available weather data for Lambton International Airport, Ontario. The model requires daily average dry bulb temperature, relative humidity, wind speed, rainfall, and snowfall as inputs.

For stover (Lambton, Ontario), the start of corn harvest was October 15, and harvesting lasted for 60 days. The number of harvest days is an indication of crop maturity and climate conditions in a region. The completion date in IBSAL was dependent upon the working rate and the amount of equipment plus climate conditions. The model considered operational delays due to rain, snow, and freezing temperatures. On average the operations were postponed 5-6 days due to weather elements. In the simulation, we assumed one working hour delay due to 1 mm rainfall. For example, a 10 mm rainfall event would delay a field operation by 10 hours. Similarly 1 mm snowfall is assumed to delay a field operation by 2 hours.

The number of machines for each operation was manually adjusted until reaching a specified completion date for that operation. For field equipment, the number of machines was varied so that the field operations were completed in winter (December 15th). For transport to biorefinery, the number of loaders and trucks was varied so that the biomass was at the biorefinery gradually over the entire year. The model outputs include the cost of each operation in \$/DMg of biomass processed in that operation. For the first three scenarios, energy input to each operation in GJ/DMg and carbon emissions from equipment in kg C/DMg of biomass processed were computed. The model calculated the quantity of harvested biomass and the quantity of delivered biomass, accounting for physical and chemical dry matter losses. The ratio of the delivered amount (Mg) to the harvested amount (Mg) was defined as "Biomass Recovery".

The number of field working equipment (shredders, forage harvesters, and bale movers) is greater than the number of trucks. The length of time available for field operations is much shorter than the length of time available for delivering and transporting biomass to the biorefinery. Results may vary with the input of more precise data.

Annual tonnage of biomass (stover) available

Table 2.3 shows the annual estimates by OPG for stover with a generating capacity of 500 MW, capacity factor of 5%, and 100% co-firing corn stover. The base load of electricity is provided by nuclear and hydroelectric. Biomass is only used in the case of emergency at peak hours to fill in the gaps. The annual heat demand of the OPG (Lambton generating station) is 2211900 GJ (detail of calculation in Appendix A). Corn stover annual demand is 124264 DMg. This quantity requires more than 21462 ha of net farmland producing stover. Note that in this calculation we assume 100% of collected biomass is available to the biorefinery. The supply area depends upon the fraction of land used for grain production. In Ontario region, corn crop constitutes 18% of the total farmland. And the supply area for stover is more than 932,000 ha.

Capacity factors of 25, 50 and 100% will increase the biomass demand significantly. For instance, assuming a capacity factor of 25% the heat demand of the biorefinery will increase to

1.1×10^7 GJ and the demand of the corn stover will increase to 6.2×10^5 Mg. With a capacity factor of 50 and 100 % the heat demand will be 2.2×10^7 and 2.38×10^7 GJ respectively and the demand of corn stover will be 12.4×10^5 and 25×10^5 Mg respectively.

BIMAT (Biomass Inventory Mapping and Analysis Tool)

BIMAT is an online mapping application provided by Agriculture and Agri-food Canada. It provides useful data of land, crops, area, location and map of the region for researchers and experts in agriculture. In this case study, BIMAT was applied to investigate the available stover in the Lambton GS environment. Initially, the radius around the Lambton GS is considered as the input of BIMAT as well as the tonnage of available stover. Area and the towns involved were the outputs, as shown in Table 2.4. This information helped us to realize how far we should move away from the biorefinery to provide the required biomass, matching supply with demand. Figure 2.9 demonstrates the outputs of BIMAT on the map.

We have also used the tonnage of biomass around some cities as inputs to BIMAT. In order to provide 50,000 Mg biomass around a city, we should know how much land is needed.

The outputs from BIMAT showed the area, the maximum collection radius around the depot, and the rail distance from the depot to the biorefinery (Lambton Station). As seen in Table 2.4, for example, 1600 km^2 of land is needed to provide 50,000 Mg stover in the city of Woodstock, but 12000 km^2 of area is required to provide the same amount of stover in the city of Sutton. Moving from Southern Ontario towards Northern Ontario would reduce the availability of biomass.

Harvest timelines

Figure 2.10 depicts the harvest timelines of several major crops in Ontario. The wheat growing season in Ontario is from April to mid July and the harvesting season is from July to mid August. After harvesting the wheat, the weather from mid-August to mid-October shall be good enough to provide the best opportunity for harvesting the residues. The soybean growing season is from mid-May to mid-September, and the harvest season is from September to mid-October. After that it is time to plant winter wheat. The growing season of corn is from mid-May to mid-October, and it is harvested from mid-October to mid-December. Farmers should harvest corn as soon as possible during that time period in order to avoid the snow.

The model requires initial moisture content of biomass associated with each unit size farm. Moisture content conditions are similar in Ontario, Canada and Wisconsin, USA (Savoie et al., 2004). Moisture content varies from 75% (wet basis) on September 1 to 55% (wet basis) on October 14 in Wisconsin (Shinners et al. 2003). Moisture content decreased as the harvest season progressed.

To simulate the chain of operations, a unit farm (100 ha size) is assumed to be serviced by a workstation for a period of time. The workstation consists of an operation (and relevant machine) such as raking, loading a truck, transporting, and so on. Table 2.5 provides more details about the capacity of common road trailers in Ontario. The workstation is represented by a delay time (processing time). The delay time for each workstation is calculated from a machine's rated performance or capacity. An item (or a unit farm) enters the workstation spends time equal to the delay time in the station and then exits. The items are queued if the workstation is busy or is not available. Costs, energy, and emissions associated with a workstation are assigned to the farm unit. Table 2.6 shows the net yield of removable stover, the area under the crop, and total supply area.

Equipment used

Table 2.7 lists the operational aspects and the costs associated with the equipment used in the simulation. The choice of the equipment type is based on the proposed operations in Figure 2.2. The size, capacity, and working rates are typical of commercial farm operations.
The amount of fuel for powered equipment was calculated using equation (2.1) (ASAE 2001).

$$F = (0.73)(0.305)(3600)\,pnh \qquad \text{(2-2-1)}$$

where F is fuel used for equipment (L), p is the rated power (kW), n is the number of equipment to get the operation done, and h is the length of time (h) the operation lasted.

Input data – cost, energy and carbon emission

Cost data are a major input to the model. Table 2.8 lists the fixed and variable costs of transportation for different types of transportation in Ontario. Sokhansanj and Turhollow (2002) described the standard procedure in developing the cost data. ExtendSim can incorporate fixed costs and variable costs in the model. For most of the scenarios we combined fixed costs and operating costs to arrive at a custom rate. The costs of barge, railroad and truck scenarios (in $/Mg) are compared in Figure 2.11.

The costs ranged from $0.87/DMg for shredding stover to more than $23/DMg for shipping the bales. In addition to distances, the cost was sensitive to the net yield of biomass, the operational speed, and efficiencies of equipment.

For the first three scenarios, the energy input per unit of biomass supply ranged from 370-799 MJ/DMg. Considering the energy content of 16,000-18,000 MJ/DMg for biomass, the energy input for collection, storage, and distribution of biomass amounts to roughly 2-4% of the energy content of the produced biomass. Trucks are major energy consumers among the equipment.

An energy content of 145 MJ/ L for diesel fuel was used to convert from liters of fuel to MJ. West et al. (2002) lists the carbon emission factor for diesel-fueled equipment as 21.95 kg C/GJ. This value includes 18.9 kg C/GJ at the point of fuel combustion and 3.03 kg C/GJ for the production and transport of fuel. We used these factors to calculate the powered-equipment's net energy consumption and net carbon emissions. Total emission factor for a supply system ranged from 36-53 kg C/DMg biomass processed. As expected, trucking and auto collecting emitted the most carbon while raking or shredding that used low powered equipment produced the least carbon emissions.

2.4 Results

IBSAL has provisions to predict biomass recovery. We defined biomass recovery as a percentage of the collectable biomass delivered to a biorefinery. The recovery represents probable dry matter losses due to physical or chemical changes in the biomass during its handling and storage. Physical losses may originate from breakup of the fragile components of the plant parts such as leaves and husks and small stems. Chemical changes are due to biochemical break up of carbohydrates into gaseous products and heat. Dry matter losses are estimated using the equations for dry matter losses for forage and the methods outlined in Sokhansanj and Turhollow (2004). Therefore, the required biomass to meet the demand from the OPG plant needs to take the percent dry matter loss into consideration, as indicated in Table 2-9.

The investigated supply systems can be ranked in terms of cost, energy input, or carbon emissions. Figure 2.12 depicts the overall delivery costs of biomass. Direct scenario was shown to have the least cost at about $37/DMg, and this value could be further reduced by about $4.5/Mg if raking and shredding operations are eliminated. The costs may rise by $2-3/DMg if tarping of the stacked bales is included. Tarping has proved to be an effective method of minimizing the effect of rain and snow on hay stacks. Ensiling cost is either equal to baling or lower than baling. Most of the ensiling cost is in the silo structure and in transportation.

It shall be noted that the output data presented in Table 2.10 are sensitive to bulk density and moisture relations for biomass. Besides, the working rates and equipment power consumption affect timeliness and costs.

2.4.1 Scenario #1 (Base Case Scenario):

The base case scenario is the most common and practical in the Ontario region based on the availability of the machinery and resources. After shredding the corn stover, the round baler is used to make the bales. Then the loader loads the bales on the small flat bed truck inside the farm. The small flat bed truck is used to move the bales for 1.6-3.2 km to the farm side. The same loader unloads the bales on the farm side and stacks the bales there. In the next step, the loader is used for loading the 12.2 m large truck. The data related to the locations of biomass growers are not available in Ontario. Therefore, it is assumed that the average distance of the farms to the gate of Lambton Generating Station (GS) is 40 km.

The number of machinery needed in this scenario may be summarized as follows: 16 shredders, 57 round balers, 11 loaders, 4 flatbed trucks, 17 large trucks.
To meet the demand of the Lambton GS, the amount of biomass required to be harvested is 160,123 Mg, taking percent dry matter loss of 22% into consideration. The total cost of the supply chain for the customer (considering machinery rental) is $37/Mg, and transportation

accounts for about 50%. The total energy consumption is 483.2 MJ/Mg, with 19% attributed to transportation. The total CO_2 emission is 33 kg C/Mg.

2.4.2 Scenario #2 (Central Storage Scenario)

In this scenario after shredding and round baling the corn stover, the auto collector (stinger stacker) is used to transport the bales to the farm side. On the farm side, the loader is used for loading the bales on the large trucks. Then the large trucks are used for transporting the bales from the farm side to the central storage. The distance from the farms side to the central storage is assumed to be 40.2 km on average. In this order, a sufficient supply of material is stored for the power plant. According to the demand and the timeline, loaders load the large trucks to transport bales to the Lambton GS. Moreover, it is assumed that the distance from the central storage to the gate of the power plant is 40.2 km.

The number of machinery needed in this scenario may be summarized as follows: 17 shredders, 56 round balers, 29 auto-collectors, 4 loaders, 17 large trucks.

To meet the demand of the Lambton GS, the amount of biomass required to be harvested is 155,730 Mg, with percent dry matter loss of 20%. The total cost for the customer is $49/Mg. The total energy consumption is 727 MJ/Mg, and the stinger has the highest energy consumption among all of the items in the supply chain (at 24%). The total CO_2 emission is 49 kg C/Mg.

2.4.3 Scenario #3 (Direct Scenario)

In this scenario, neither farm storage nor central storage is used. After shredding, a square baler is used to make the bale. Then the loader loads the bales on the large truck in the farm and bales are transported directly to the storage at the OPG power plant. In comparison to the first two scenarios, this scenario is more economical. However, sometimes it is not practical to send a large and heavy truck to the farm because of bad weather conditions.

The number of machinery needed in this scenario may be summarized as follows: 15 shredders, 18 square balers, 4 loaders, 5 large trucks.

To meet the demand of the Lambton GS, the amount of biomass required to be harvested is 151,141 Mg, considering percent dry matter loss of 18%. The total cost for the customer is

$33.7/Mg. The total energy consumption is 337 MJ/Mg, and transportation has the highest energy consumption among all of the items in the supply chain (at 27%). The total CO_2 emission is 23 kg C/Mg.

The direct scenario, which involves neither side storage nor central storage, costs about 30 percent (or $13/Mg) less than the central storage scenario and 10 percent less than the base case scenario. The central storage system is an attractive option because it is more probable to have a reliable amount of biomass in storage throughout the year for the power plant, but the costs of construction and transportation increase the overall costs.

The comparison of the base case scenario with the central storage scenario showed that using the new technology of an auto-collector would save approximately 6,500 Mg biomass in the supply chain. However, it would lead to higher energy demand and emit more carbon into the environment. The central storage scenario requires more transportation, which causes more dry matter losses by 1500 Mg. The least amount of dry matter losses occurs in the direct scenario. Therefore, in comparison to other scenarios more biomass would have been transported. Hence, the number of trucks in the direct scenario is greater than the other scenarios.

2.4.4 Scenario #4 (Barge Scenario)

In this scenario, firstly, corn stover is shredded and baled. Then, the bales are moved to the side of the farm by using small flatbed trucks. At that point, loaders are used to put the bales on the truck. Then the bales are transported 100 km to the waterfront by using the truck. It is assumed that the distance between the waterfront in the supplier side and the OPG side is 150 km. It is assumed that a barge is used for transportation on Lake Huron. This barge has the capacity of loading 2500 bales in each trip. When it arrives at the OPG side, loaders are used to unload the ship and load the trucks. Finally, trucks move the bales 1.5 km to the OPG gate and loaders unload the bales there.

Initially, to meet the demand of the Lambton GS, the amount of biomass required to be harvested is 172,480 Mg, considering percent dry matter loss of 28%. Eight barges are needed to deliver the biomass within a 6-month period, with an assumption of 24 working hours per day. The total cost for the customer is $94/Mg, with the cost of shipping calculated to be $23.5/Mg.

2.4.5 Scenario #5 (Railroad Scenario)

Similar to the harvest part in scenario #4, in this scenario, after shredding and baling, biomass is loaded on a small flat bed truck and move to the side of the farm. Loaders are used to unload the flatbed trucks and load the big trucks. From the side of the farm to the railroad station bales are moved by the big trucks for 10 km. Then loaders are used to unload the trucks and load the box cars. Railroad transport the bales for 150 km. Loaders are used to unload the box cars and then load the truck. Finally, trucks transport the bales for 2.5 km to the gate of OPG to be unloaded by the loaders.

To meet the demand of the Lambton GS, the amount of biomass required to be harvested is 170,686 Mg, with percent dry matter loss of 27%. The total cost of this scenario is $81/Mg, and the cost of transportation by railroad is $25/DMg. One locomotive is required to transport all of the bales, making 264 trips within 6 months. It is assumed that we can use the railroad transportation 24 hours per day and seven days per week. It was determined that 100 box cars must be attached to the locomotive.

Both the barge and the railroad scenarios have advantage vs. the truck scenario because the working hours of the barge and the railroad can be 24/7. The cost of the barge and railroad scenarios are significantly higher than other scenarios because it is more cost efficient to use barge and rail road for distances that exceed 150 km. The cost of the barge scenario is higher than the railroad scenario as a result of the more costly transport to the waterfront. Nevertheless, during the winter Lake Huron and St. Clair River might be frozen, which call for alternatives to barge transport.

2.5 Sensitivity Analysis

Sensitivity analyses were performed in several aspects such as harvestable yield, bale density, storage location, and the demand for biomass (corn stover). Based on literature review (Section 2.1.1), the sustainably available yield of corn residue can range from 2.2-3.2 Mg/ha depending on cultivation practices such as crop rotation. A value of 3.2 Mg/ha was used initially for the calculations.

A sensitivity analysis was then performed using a value of 2.2 Mg/ha. As shown in Table 2-10, decreasing the harvestable residue from 3.2 to 2.2 Mg/ha would increase the required agricultural land area by 45% from 38832 ha to 56483 ha in order to meet the same biomass demand of 124262 Mg from the OPG power plant. The increased land area does not affect percent dry matter loss due to machinery handling; however, it would lead to a corresponding increase in energy consumption, for instance, from 483 to 773 MJ/Mg and CO_2 emission from 33 to 53 kg/Mg, respectively, for scenario #1. The operating cost of machinery is estimated to increase by about 10% while the fixed cost remains unchanged, thus resulting in an increase in total cost, in $/Mg by 10%

Having denser bales makes the transportation more cost-effective as more biomass can be transported with the same volume. However, more powerful tractors are required to make denser bales, thus increasing the costs. Sensitivity analysis on the bale density reveals that the minimum cost would occur with the optimum bale density ranging from 60-192 kg/m^3. Is it assumed that the moisture content of the stover at the harvest time is 35% (wet basis).

For the central storage scenario, sensitivity analysis on the location of the storage was done. Bales are usually transported to the central storage by farmers who own small trucks. And from the central storage bales are transported to the power plant by large trucks. Due to the economy of scale, it is beneficial to use large trucks rather than small ones. The results showed that the closer the storage to the farms the lower the transportation costs will be.

The effect of biomass demand of the biorefinery is investigated for all of the scenarios. By doubling the biomass demand to 275,500 Mg, the cost of the supply chain would decrease by $4, $7 and $3/Mg respectively for scenarios #1, 2 and 3. However, this does not imply that the number of machinery needs to be doubled. In conclusion, increasing the biomass demand will make the whole supply chain more cost-effective.

2.6 Conclusion

The broad output of this case study is a comparison of the economic and environmental impacts of the five scenarios, in terms of calculated energy consumption, carbon emission, dry matter loss, and cost. The calculations were based on assumed net yield of 3.2 dry DMg/ha for corn stover. The operations were simulated in such a way to make sure all field activities are completed in the fall, excess biomass is stored during the year, and the biomass is gradually transported to the biorefinery. At the biorefinery site, storage is provided to ensure OPG has a sufficient amount of biomass during the year.

The net amount of annual biomass demand at the power plant is estimated to be 124,264 dry metric ton (Mg). For Scenario 1 the amount of biomass required to be harvested is 160,123 Mg per year at $37/Mg. For Scenario 2 the amount of biomass is 155,730 Mg per year at $49/Mg. For Scenario 3 the amount of biomass is 151,141Mg per year at $33.7/Mg. The differences in the amount of biomass and cost are due to the assumed dry matter loss and transport distance. For the barge scenario (option 4) 172,480 Mg biomass is required per year to meet the OPG demand. The cost was estimated to be $94/Mg, and eight barges are used to deliver the entire biomass to the OPG power plant within a time period of 6 months. For the railroad scenario (option 5), 170,686 Mg biomass is required per year. The cost was estimated to be $81/Mg, and all the biomass could be delivered using 264 trips. The simulation model shows that it is feasible to assemble a lower-cost supply system for biomass when compared to the existing baling system.

Energy input to the system was generally low in the range of 2-4% of the energy content of the biomass. The emitted carbon (CO_2 equivalent) from powered equipment ranged 23 - 50 kg C/DMg of biomass. Carbon emissions from the central storage scenario are high due to the need for transporting the biomass a longer way.

Due to the denser bale production and higher efficiency of the square baler, the number of square balers required is significantly less than the number of the round balers required, given the same biomass demand.

It shall be noted that the availability of more robust data on the location of the farms, bulk density, changes in dry matter as influenced by handling and storage conditions and equipment performance could improve the accuracy of modelling and simulations.

The moisture content of corn stover is as high as 80% during the early harvest season and it decreases to 15% towards the end of harvest season (Leask & Daynard , 1973). In this study, the working rates of the equipment in the field and off the field including truck and wagon capacities were based on advertised throughputs and consultations with experienced operators. We also assumed equal densities for round and square bales of stover, but this may not be the case and needs further investigation.

Figure 2-1 OPG generating stations – Lambton (by permission from OPG)

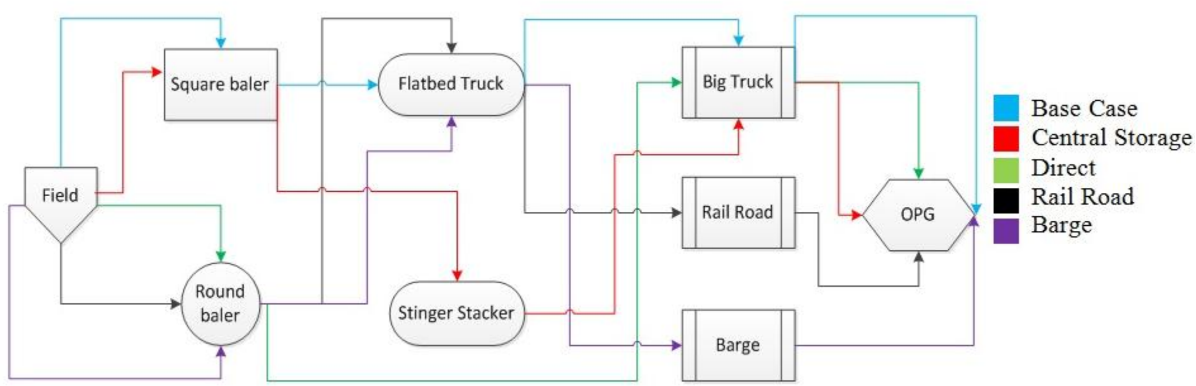

Figure 2-2 Overall schematic of the five supply chain scenarios – major options for biomass collection, storage, and transport

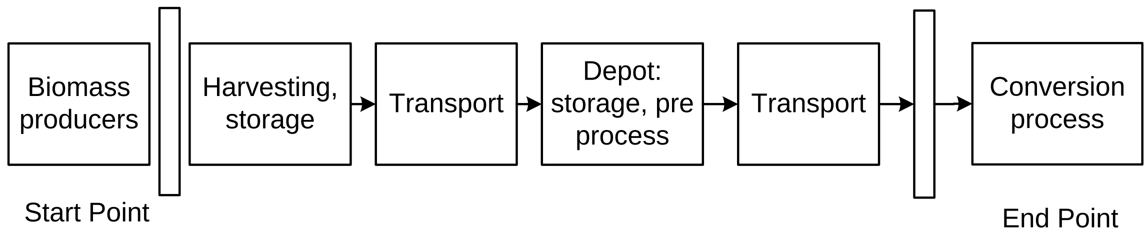

Figure 2-3 The simulated biomass supply chain in the IBSAL model

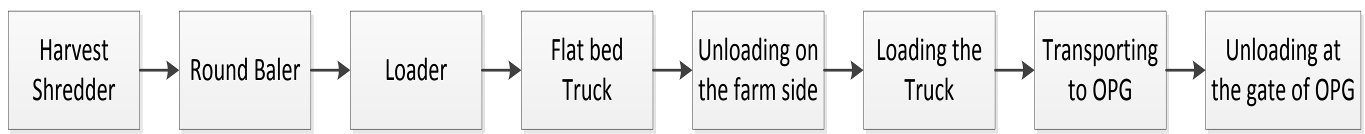

Figure 2-4 Base case scenario

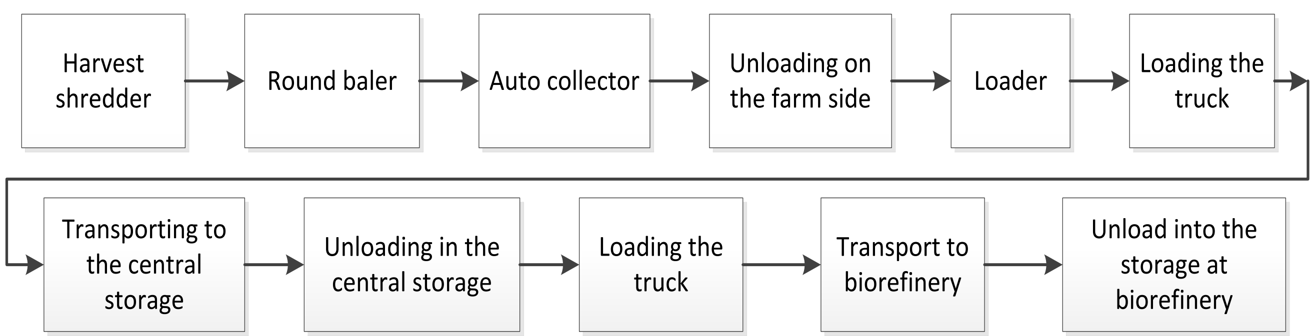

Figure 2-5 Central storage scenario

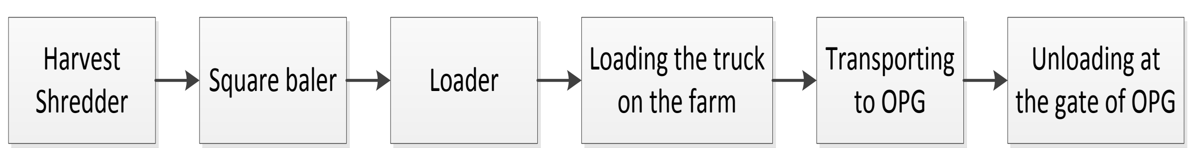

Figure 2-6 Direct scenario

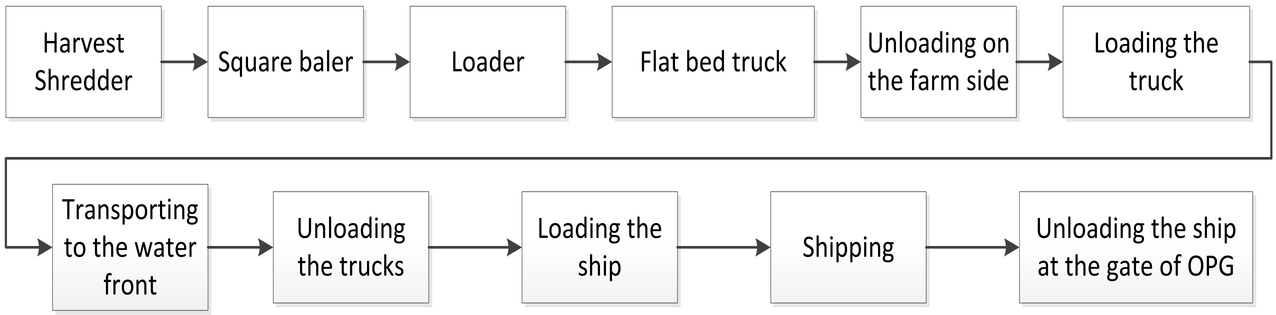

Figure 2-7 Barge scenario

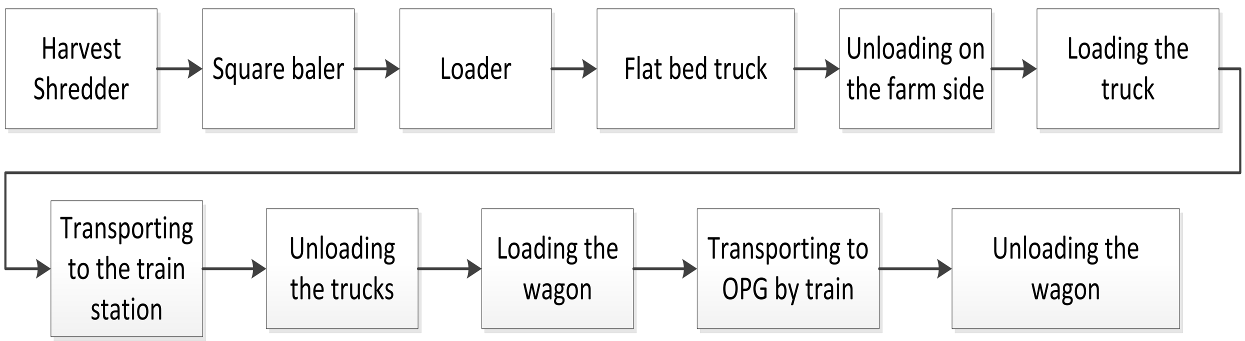

Figure 2-8 Railroad scenario

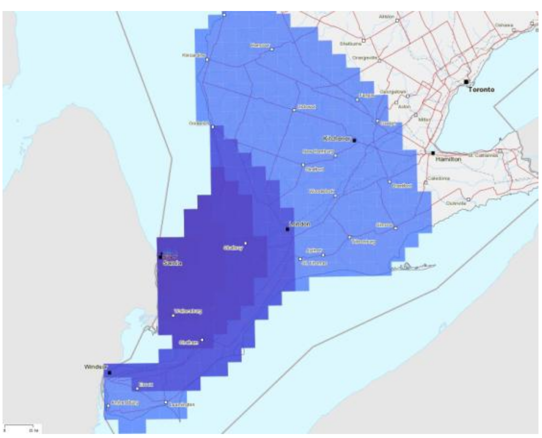

Figure 2-9 BIMAT outputs – Availability of corn stover in Ontario
(by permission from Agriculture Agri - Food Canada)

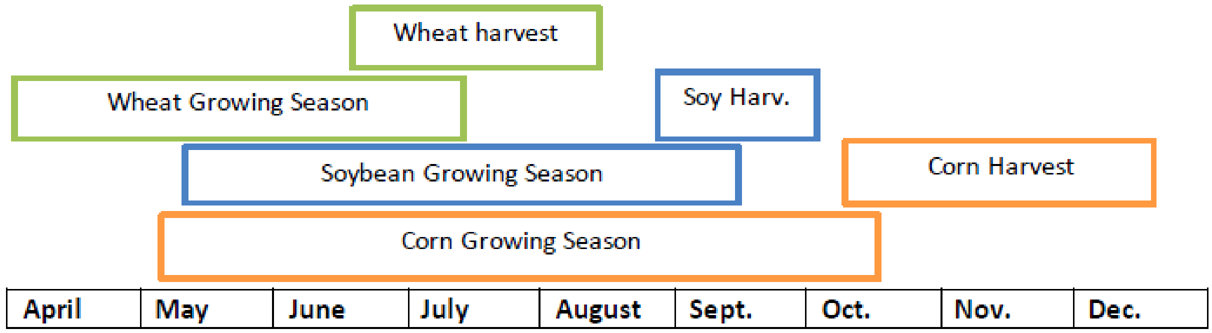

Figure 2-10 Harvest timelines in Ontario (McDonald 2010)

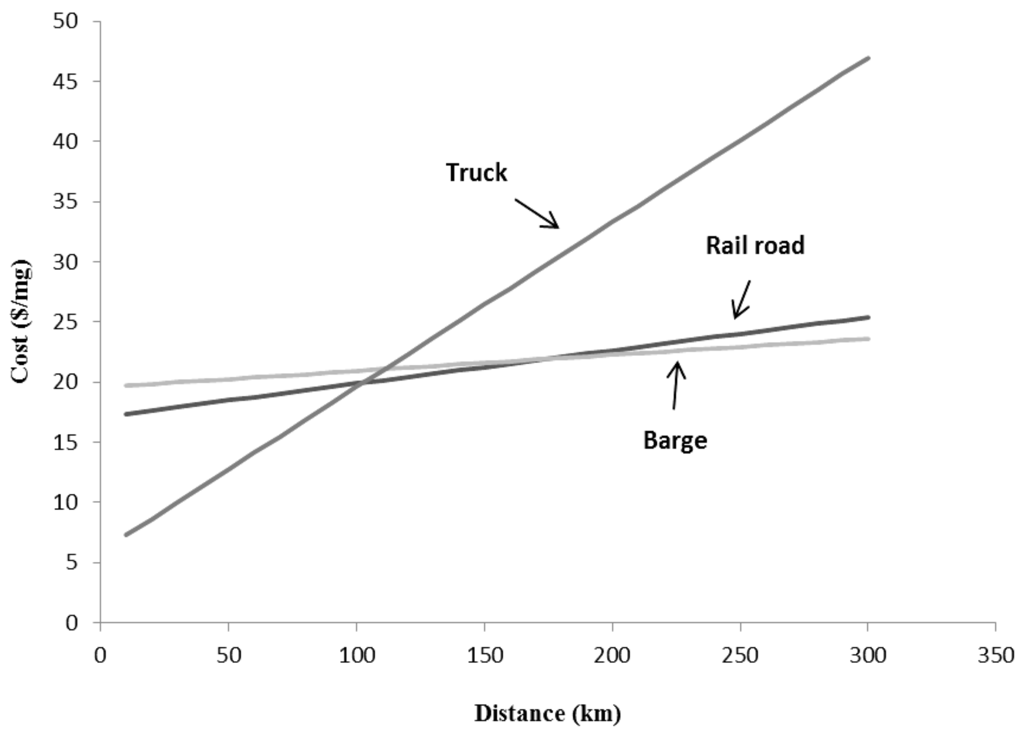

Figure 2-11 Comparison of costs of different types of transportations in Ontario

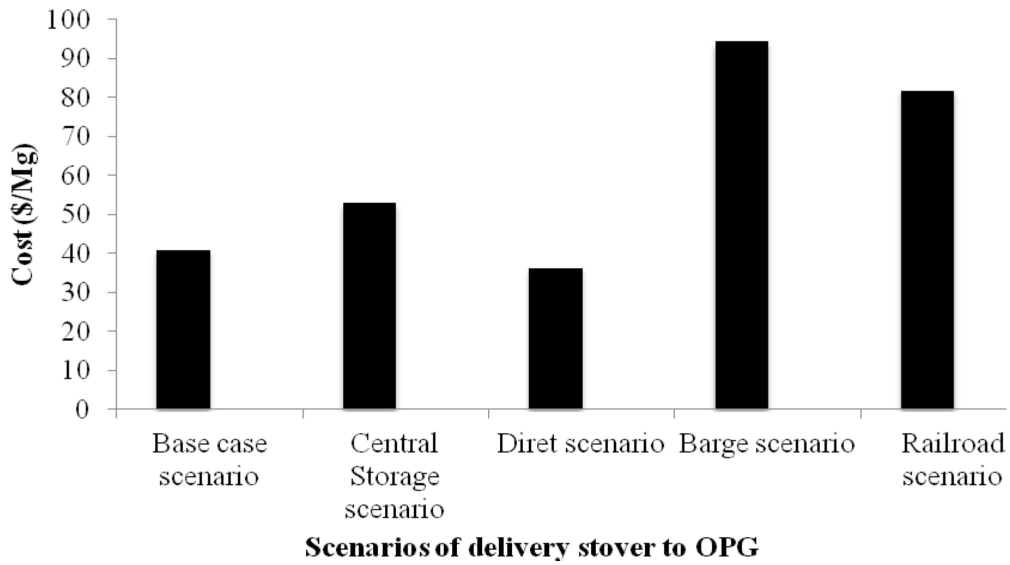

Figure 2-12 Cost of delivering stover to OPG (Lambton GS). The cost values are based on assumptions on bulk density and equipment operating efficiencies.

Table 2-1 Barge Specifications

Flag	Canadian
Port registry	Hamilton, Ontario
Capacity, Mg	9800
Usable deck space, m^2	1800
Length, m	129.6
Beam, m	22.6
Depth molded, m	9
Light draft, m	1.2
Loaded draft, m	5.8

Table 2-2 List of input data needed to conduct an analysis

Location of biorefinery and supply region	Lambton, ON
Type(s) of biomass processed	Stover
Demand on biomass and delivery schedule (daily-monthly), dry Mg/year	124,264
Land required to provide OPG biomass demand (A) (ha)	38,832
Total cultivated corn grain in land in the region (B) (ha) [1]	822,465
Ratio of A/B	0.047

Table 2-2 List of input data needed to conduct an analysis

Fraction of crop removable from land with respect to soil conservation	0.45
Progress of harvest - beginning grain harvest date and days of harvest[1]	Oct 15; 60 days
Typical moisture content of stover at the time of harvest (wet mass basis)	35%
Winding factor – for calculating transportation costs[2]	1.25
Climate data - daily average temperature, relative humidity, wind speed, solar radiation, rainfall, snow fall[3].	

[1] Data from http://www.omafra.gov.on.ca/english/stats/welcome.html

[2] Jenkins and Sumner (1986) has used a winding factor based on the ratio of sum of laterals in a right angle triangle to hypotenuse (the maximum value will be 1.41).

[3] Climate data for Lambton Ontario, are from environment Canada website (available from: http://climate.weather.gc.ca/).

Table 2-3 Annual tonnage of biomass (stover) available with the indicated radius from the Lambton Sarnia OPG power plant. The area and countries that grow the stover are listed. (Data extracted from BIMAT; http://www.agr.gc.ca/atlas/bimat)

Radius around Lambton Station, km	Available stover, Mg	Area, km^2	Additional towns involved
25	8,474	800	Petrolia – Plympton Wyoming
50	46,645	3,200	Forest – Lambton Shores -
75	126,333	6,800	Strathroy – Chatham
100	214,968	12,700	Ridgetown – Blenheim – Tilbury – Lakeshore – Windsor – Essex-
200	531,951	34,600	Kincardine – Listowel – Kitchener - Guelph – New Hamburg – Stratford – Woodstock – Aylmer - St. Thomas – Tilsonburg – Simcoe – Fergus – Brantford – Mitchel – St. Mary's – Elmira – Waterloo – Cambridge – Ayr-Paris – Brant –Rockwood – Mount Forest – Durham –Hannover – Walkerton – Saugeen Shores – Palmerston

Table 2-4 Annual tonnage of biomass (stover) available at depots along the rail line from Sarnia towards the northeast (Strathroy, Woodstock), the north (Milton, Alliston, Sutton) and the south (Chatham) with the indicated radius from the Lambton Sarnia OPG power plant.
Data extracted from BIMAT (25% participation).

Depot location along the rail-line from Lambton Station	Stover available at the depot, Mg	Rail distance from the depot to Lambton Station, km	Maximum collection radius around the depot, km	Area, km^2
Woodstock	50,051	153	23	1,600
Strathroy	51,148	71	24	2,000
Chatham	52,251	150	30	2,700
Milton	50,748	244	50	6,600
Alliston	50,076	300	60	10,600
Sutton	50,100	300	64	12,000

Table 2-5 Capacity of common road trailers in Ontario (Oo et al., 2012c)

Trailer combination for bale size (1.2 m x 0.9 m x 2.3 m)	Standard-density Bale		High-density Bale	
	# Bales	Weight (Mg)	#Bales	Weight (Mg)
16.2 m (53 ft) Flatbed	42	17.64	42	22.05
B – Railroad	51	21.42	51	26.76
16.15m Walking Floor Van Body	39	16.38	39	20.48

Table 2-6 Net yield of removable stover, and calculated area under the crop and total supply area

Net yield of removable stover (Mg/ha)*	3.2
Working days	365
Annual demand (Mg)	124,262
Cultivated area required (ha)	38,832
Supply area (ha)	932,000
Number of farms with area >162	8,519
Number of farms with area 53-161 ha	16,230
Number of farms with area < 53 ha	27,201

* The term “net yield” may also be called “sustainably available yield”. Based on literature review (Section 2.1.1), the value can range from 2.2-3.2 Mg/ha. Here, a value of 3.2 Mg/ha was used initially for the calculations.

Table 2-7 Equipment and storage specifications

Machinery and buildings	Specifications	$/h Variable	$/yr Fixed	$/h CR1	$/h CR2
Shredder	S 7, W 4.2, E 0.85	23.26	1235	8.39	37.24
Rake	S 8, W 2.1, E 0.80	8.05	365.8	5.47	34.32
Square baler	S 6, W 4.2, E 0.85	39.15	4080	45.95	88.53
Round baler	S 6, W 2.1, E 0.75	39.15	4080	45.95	88.53
Forage harvester – SP	S 9, W5, E 0.90	73.38	6203	83.72	83.72
Bale mover- SP	SF 10, SE 12, D 2, E 0.9, NB 10	111.18	6483	121.96	121.96
Forage wagon	SF 20, SE 25, D 2, CL 3.5, NB14	13.35	1501	15.85	49.57
Bale loader - Tractor 120 hp	LT 1.0, UT 0.5	59.85	4646	64.49	64.49
Silage loader – Tractor 120 hp	LT 0.5, CL 0.2	42.00	2991	44.92	44.92
Flatbed truck	SF 40, SE 45, PT 10, NB 24	29.19	19597	41.68	41.68
Silage truck	SF 60, SE 65, CL 14, UT 0.5	29.76	2486	42.56	42.56
Loader – Stackhand 60A	M 3.85, S 9, W 5, E 0.85	20.84	3639	27.12	60.84
Grain truck	CM 87.5	73.27	18196	76.91	76.91
Grinder – SP	CT 22	39.46	24414	48.82	48.82
Silage pit	L 35, W 20, H4, d 160	0.19	4758	-	-
Tractor 85 hp	for shredder, rake	26.51	2340	28.85	28.85
Tractor 120 hp	for forage wagon	32.43	3321	33.72	33.72
Tractor 160 hp	for baler	38.43	4157	42.58	42.58

CM = capacity (m^3/load), CR1 = custom rate without power unit, CR2 = custom rate with power unit, CL= capacity (Mg/load), CT= capacity (Mg/h), D=distance travelled (km), d= density (kg/m^3), E=Efficiency (decimal), H= height (m), L=length (m), LT= loading time (min/bale, min/load), M= mass (Mg), NB=number of bales per mover or truck, PT=preparation time (min), S= speed (km/h), SE=speed empty (km/h), SF=speed full (km/h), SP=self-propelled or self-powered, T=silage compaction time (min), TT= time to tarp (min/man per stack) UT= unloading time (min/bale, min/load), W=width (m)

Table 2-8 Fixed and variable cost of different transportations in Ontario (Flynn 2007; Samson 2008; Sokhansanj and Fenton, 2006; Sorensen, 2005)

Parameters	C1($/DMg)	C2 ($/DMg/km)
Truck	6.84	0.1641
Rail	20.52	0.0333
Marine	23.52	0.0136

Table 2-9 Simulated biomass recovery

Supply system	Initial biomass (Mg)	Biomass recovery* (%)
1- Base case	160123	78
2- Central	155730	80
3- Direct	151141	82
4- Barge	172480	72
5- Railroad	170686	73

* Biomass recovery = (100 – dry matter loss)%

Table 2-10 Simulation outcomes of sensitivity analysis on sustainably available yield of corn stover using lower bound and upper bound values

Sustainability available yield 3.2 Mg/ha Required land area 38832 ha					
Scenario	Biomass required, Mg	Dry matter loss, %	Total cost $/Mg	CO_2 emission kg/Mg	Energy consumption MJ/Mg
1	160123	22	37	33	483
2	155730	20	49	50	727
3	151141	18	34	23	337
4	172480	28	94	n/a	n/a
5	170686	27	81	n/a	n/a
Sustainability available yield 2.2 Mg/ha Required land area 56483 ha					
Scenario	Biomass required, Mg	Dry matter loss, %	Total cost, $/Mg	CO_2 emission kg/Mg	Energy consumption MJ/Mg
1	160123	22	42	48	703
2	155730	20	53	72	1057
3	151141	18	37	33	490
4	172480	28	101	n/a	n/a
5	170686	27	88	n/a	n/a

n/a: the emission and energy consumption for scenarios #4 and #5 are out of scope of this study

Chapter 3: Delivery of Switchgrass to a Greenhouse in Ontario, Logistics, Cost and Dry Matter Loss

3.1 Introduction

Ontario has the largest greenhouse industry in Canada, accounting for 52% of floriculture in Canada (Bailey-Stamler. 2006). It plays a crucial role in the economy of Ontario. In North America, Ontario is the largest producer of greenhouse vegetables and the third largest producer (after California and Florida) of floriculture (Planscape report, 2006). The industry had sales revenue of 1.5 billion dollars. Vegetable greenhouses operate year-round but flower greenhouses operate 6-7 months of the year. About 75% of the greenhouses are in Southern Ontario (Hamilton-Niagara region). In particular, there is a high density of greenhouses in the Essex region and the town of Lambton.

Table 3.1 shows the area, number of operations, the type of the greenhouse cover in two sectors of vegetables and flowers in Ontario. Over the past 6 years, the number of greenhouse operations has decreased from 3000 in 2008 to 2620 in 2013. Yet, the total area under greenhouses has increased to 2178 ha in 2013. The average size of a greenhouse facility has increased from 1.06 ha in 2003 to over 1.47 ha in 2013.

Both plastic and glass are used as covers for greenhouses. Approximately 33% of the greenhouses are under glass cover whereas 67% are under plastic cover. Plastic covers seem to be more attractive for the greenhouse owners as they are cheaper in comparison with glass and more flexible. The choice of the cover material can be based on the type of the crop, weather conditions of the region, preference and experience of growers (Giacomelli et al. 1993) Heating demand induces a major operating cost, which constitutes 20-35% of the total cost of flower production, depending on the crop produced in the greenhouse. The winter months of December-February represent 58% of the total annual heating requirements (Brown. 2003).

Labor and fuel costs make the greenhouse production more costly when compared to field crop production. Fuel costs can vary from time to time and make the cost estimation difficult.

It is interesting to note that the fuel cost has decreased from 12.9% of the sales revenue in 2008 to 7.8% in 2013 (Statistics Canada 2014). Natural gas is common in greenhouses in Niagara, and in the Leamington/Kingsville regions, sometimes bunker oil is used as a substitute for natural gas. Fluctuating prices of energy motivated the growers to look for other sources of energy such as biomass, ethanol, wind, geothermal and coal options.

Switchgrass can be grown as a local energy crop and supply heat for agricultural and rural users as a sustainable substitute for natural gas. Oo et al. (2012 c) showed that fuel pellets derived from switchgrass can be produced and delivered for $11/GJ, or roughly one-third of the fuel cost of heating oil or propane. Unpelletized (baled) switchgrass could be delivered even at lower price. However, the establishment and supply of sufficient switchgrass to the end user at a competitive price remains a challenging problem. Harvesting schedule, transportation, dry matter loss and moisture content of switchgrass are some of the factors that can impact the delivery cost.

3.2 Objectives

The main objectives of this chapter are to estimate the heating demand of a typical greenhouse in Ontario and hence the amount of switchgrass (biomass) required to meet this heating demand. The IBSAL model is applied to simulate the supply chain. Other objectives include the determination of dry matter losses, costs and carbon emission.

3.3 Methodology - Input data, Assumptions and Simulation Procedure

3.3.1 Harvest Schedule, Yield, and Moisture Content

The following information represents the applicable production and logistics framework. Cave `N Rock is a common variety of switchgrass in the Ontario region (Bailey-Stamler et al., 2006). It is planted in April for the first year but is not cut for the harvest in the first year, and windrowed until late October of the following year. During the winter, farmers leave the cut crop on the land, in order to let the minerals be leached, thereby improving the combustion characteristics. In spring (April and May), farmers flip windrow over with a rake to reduce the moisture content. Switchgrass is baled once the moisture content reaches 8-9% (d.b.) which is suitable for baling. The mass of each bale is 0.4 Mg. Bales are loaded onto trucks and shipped to the storage. The bales are unloaded and stacked in storage till farmers receive orders from the end users. The yield of switchgrass is assumed to be 11.25 - 13.75 Mg/ha (Kludze et al., 2013).

Figure 3.1 illustrates the supply chain of switchgrass modeled in this study. The baled switchgrass is to be supplied from three actual production fields in Southwest Ontario to a fictitious greenhouse nearby. The following operations are included in the modeling and simulation: harvesting, raking, baling, loading, transporting, storage and unloading. The scope of the study excludes handling of the biomass at the greenhouse and feeding into boiler.

3.3.2 Weather Data

Daily temperature, snow on the ground, and daily precipitation were collected from Environmental Canada`s Historical Weather Office (Environment Canada, 2012). The data of the London, Ontario weather station was used in this study. Relative humidity and evaporation were calculated. The evaporation rate is given by Eqn (3.1) (Holman, 1990):

$$E_P = (3.21 + 0.078\,u)\,(P_s - P_v)^{0.88} \qquad (3.1)$$

where E_p is evaporation rate (mm/d), u is the wind speed (km/d), P_s is the saturation vapor pressure (kPa), and P_v is the vapor pressure (kPa).

3.3.3 Equipment Data

Based on actual switchgrass harvesting in Ontario, a New Holland 15 ft self propelled discbine Model H8060 is used to harvest the crop in October. The windrowed switchgrass is left over-winter. The windrows are flipped over in April – May with a Case International Maxxum 110 tractor pulling a Nuhn GA 4220 TH rake and baled with a Case International Magnum 215 tractor pulling a Massey Ferguson 2170 baler. In the next step, an auto collector is used to move the bales to the side storage area at the edge of the field. A wheel loader with bale grapple is used to load the bales onto 16 m large trucks. All of the bales are transported to a centralized barn for storage. Upon receiving an order from the end user, bales are re-loaded and transported to the gate of the greenhouse by utilizing a loader and large trucks.

3.3.4 Greenhouse Heating Demand

The greenhouse heating demand is primarily made up of two components – heat loss to the surroundings due to conduction and heat loss due to ventilation and infiltration.

Ventilation and infiltration heat loss

The area of the greenhouse sidewalls and greenhouse roof are 1,500 and 10,000 m^2, respectively.

Heat loss due to ventilation may be estimated using:

$$Q = \rho\, N\, V\, c\, (T_i - T_o) \qquad (3\text{-}2)$$

where Q is the ventilation and infiltration heat loss rate (kJ/h), T_i is the inside temperature of the greenhouse, T_o is the outside temperature (^oC), N is the number of air changes per hour, V is greenhouse volume (m^3), ρ is air density (kg/m^3), and c is the specific heat of air (kJ/kg°C)

Conduction and convection heat loss

Conduction heat loss occurs through the greenhouse cover (roof and sidewalls), and it may be estimated using Eqn (3.3):

$$Q = UA\, (T_i - T_o) \qquad (3\text{-}3)$$

where A is the surface area of the greenhouse cover (m^2), U is the overall heat transfer coefficient which takes into account conductive heat transfer and convective heat transfer ($W/m^2.^oC$).

A fictitious greenhouse is assumed in the simulation. Biomass is assumed to be the only fuel source to satisfy the heating demand of the greenhouse (that is, without co-firing). The dimensions (height, width and length) of the greenhouse are assumed to be 3 m, 100 m, and 100 m respectively. Radiation heat loss is assumed to be negligible as compared to conduction and ventilation. The overall heat transfer coefficient is assumed to be 4 $W/m^2.°C$ (Aldrich 1989).

The efficiency of the boiler is assumed to be 70%.

The inside temperature of the greenhouse can range from 16–27 ^{o}C depending on the time of the day (daytime vs. nighttime), setpoint strategy for temperature control and the type of crop (Nelson, 1991). In the simulation, it is assumed to be 19 ^{o}C on average. The daily outside temperatures were taken from the 2012 weather records for London, Ontario, as obtained from the website of Environment Canada.

3.4 Results and Discussion

The heating demand of the greenhouse as well as the IBSAL model outputs in terms of the amount of biomass required, dry matter loss, costs and carbon emission are presented and discussed in this section.

3.4.1 Dry Matter Loss in the Supply Chain

The variables that a user adjusts in IBSAL consist of biomass yield, the harvest fraction, harvest schedule, and the weather condition. Users have access to a library which includes different machinery. Machinery in the model can be chosen according to the defined scenarios. The whole supply area is divided into harvest fractions. According to the harvest schedule field operations are done on each of the harvest fractions. The model was run for different values of the variable parameters. For each unit operation the IBSAL model calculates a loss in dry matter due to mechanical or chemical breakdown. Table 3.2 shows the output of the IBSAL model simulation in terms of dry matter loss and biomass recovery in the supply chain of the switchgrass.

Leaving the switchgrass in the field over winter can leach out some of the minerals that contribute to clinkering in combustion systems. Therefore, farmers cut the crop in the late October and leave it during the winter. In spring (April – May) the farmers flip switchgrass with a rake to increase drying, and then bale it. Otherwise, baling switchgrass after cutting in fall will preserve more of the minerals in the biomass. Figure 3.2 shows the dry matter loss in each item of the supply chain.

3.4.2 Cost of the Supply Chain

In this study the cost of each operation was considered using custom rate data from Bagg et al. (2009). Figure 3.3 depicts the logistics costs for custom rate. Where possible, it is more economical for farmers to contract out the logistics operations compared to owning the equipment.

The average cost of transportation of agricultural biomass in Ontario is reported to be about $40- 50/Mg (Oo 2012 a) which is comparable with the simulated outputs. The starting point of the simulation is harvesting and the end point is at the gate of the greenhouse. The minimum cost of production over a five year period was estimated to be $52/Mg (Perrin et al., 2008). Kludze et al. (2013) calculated the breakeven cost of production as $62.6/Mg at 11.2 Mg/ha.

3.4.3 Heating Demand of Greenhouse

The calculated annual heat loss through conduction only was 14369 GJ, and the annual thermal load of the greenhouse (conduction plus ventilation heat losses) was calculated to be 20730 GJ. Figure 3.4 shows the monthly heat loss of the greenhouse through conduction and ventilation, and hence the total heat losses. During June-August 2012, the temperature outside of the greenhouse was higher than 19 °C; hence there are no heat losses to the surroundings.

3.4.4 Biomass Supply to Meet Greenhouse Heating Demand

The amount of switchgrass required to meet the heating demand of the greenhouse was estimated to be 2177 Mg, which would be equivalent to 7331 large square bales of switchgrass. Three farms were assumed and identified to be the suppliers. Based on an estimated 35% of dry matter loss in the supply chain (Table 3.2), a quantity of 1421 Mg would be deliverable at the gate of the greenhouse.

Factors that affect the amount of dry matter loss are the biomass moisture content, storage regime, the weather conditions and the type of biomass (Rocky, 2009). Since a certain fraction of biomass is lost in each step of the supply chain, it is desirable to shorten the supply chain wherever it is feasible.

It is vital to store the bales and provide a reliable supply of biomass for the end user. One option to compensate for the lost biomass of 756 Mg is to add another farm to the existing three farms. The size of this additional farm was determined to be 99 ha. An alternative strategy is to reduce the dry matter loss. A more protective storage system can make this work; for instance, placing the bales on a concrete pad to avoid spoilage rather than on the ground with direct contact with soil. Sending the bales directly to the end user and omitting the central storage could be another option. This option can avoid 189 Mg of dry matter loss.

3.4.5 Effect of Harvest Schedule on the Logistics

The spring baling method, despite the lower yield, would lead to improved quality due to the loss of moisture and minerals. Some minerals can cause the problem of slagging and fouling in the boiler. It is therefore desirable to wait until spring and reduce the probability of occurrence of these problems (Alder et al. 2006). In the spring the concentrations of Cl, K, P, and Mg have been reported to decrease by more than 50%, whereas the concentrations of Ca, S, and N decreased to lower than 25% of the concentrations in the fall (Miles et al., 1996).

Moisture reduction is advantageous as biomass will become lighter, thus saving some of the transportation costs. For instance, moisture reduction from fall (16-17%) to spring (12-14%) at harvest resulted in a cost saving of about \$1/Mg. Besides, as the ash content decreased from 5 to 3% from fall to spring, the switchgrass had improved quality and could combust more efficiently in the boiler (Samson , 2007). Ogden et al. 2010 showed that the oxygen level increased in switchgrass when it was harvested at the end of winter or early spring, resulting in better combustion.

3.4.6 Energy Input and Carbon Emission, Supply Chain

This report considers the consumed fossil fuel from harvest and transport equipment operations to determine the energy consumption, but other sources of energy such as labor, fertilizer, planting were not taken into consideration as they were too variable for a fictitious greenhouse. Total energy consumption of the scenario is 927 MJ/Mg. The operation of the tractor to pull the trailer to transport the bales to the storage consumes the highest amount of energy, at 483 MJ/Mg. The amount of carbon emitted is 63.5 kg CO_2. Transportation constitutes the major component with 33 kg C/Mg.

3.5 Conclusions

The IBSAL model was used to simulate the supply chain of switchgrass from three existing farms to a greenhouse located in Southern Ontario. The supply chain was investigated from harvest to the gate of the greenhouse (including harvesting, raking, baling, loading, transporting, and storage), but the production of switchgrass was not considered in the study. Assuming a higher heating value (HHV) of 18 GJ/Mg for dry switchgrass, the energy input to harvest and transport the biomass was found to be less than 1% of the HHV of the dry switchgrass.

Based on conduction and ventilation heat losses, the annual heating demand of a greenhouse was estimated to be 20730 GJ. The amount of switchgrass required to meet this heating demand was estimated to be 2177 Mg. As the dry matter loss was determined to be 805 Mg, the three farms will not be able to produce adequate switchgrass to supply the 10,000 m^2 (1 ha) greenhouse. Options including the addition of another farm or implementing ways to reduce the dry matter loss were suggested to compensate for this shortage of biomass supply.
Cost, energy consumption and carbon emission associated with the supply chain were found to be $66/Mg, 151.3 MJ/Mg and 10.4 kg CO_2/Mg, respectively.

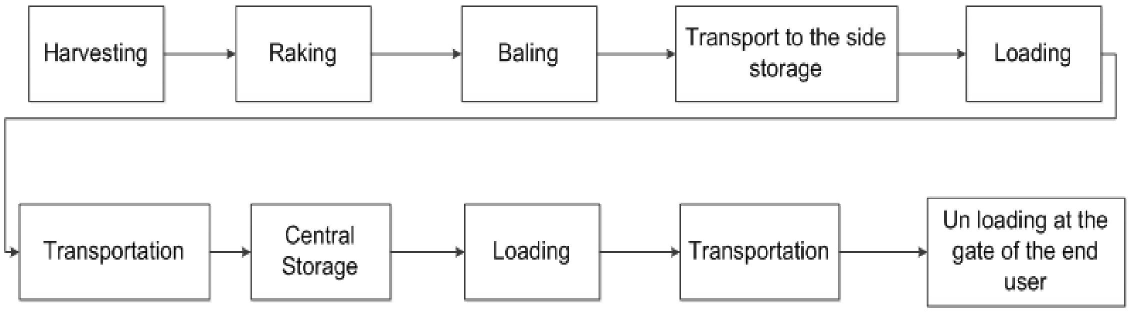

Figure 3-1 Logistics of the biomass supply chain

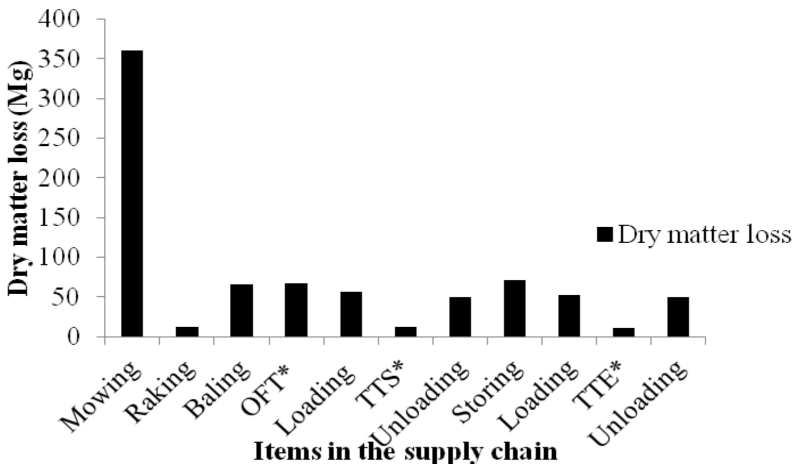

Figure 3-2 Dry matter loss in the supply chain (OFT On Farm Transportation; TTS Transportation to Storage; TTE Transportation to End user)

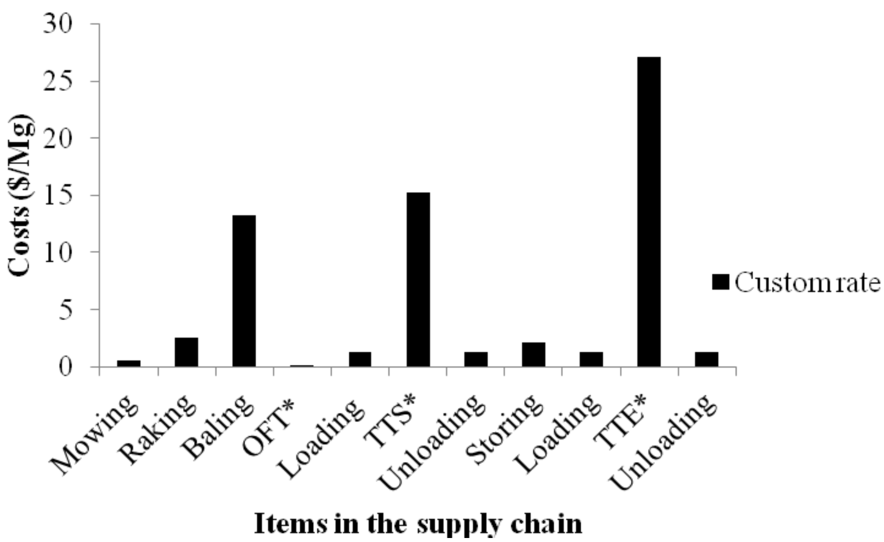

Figure 3-3 Custom rate costs for each supply chain operation

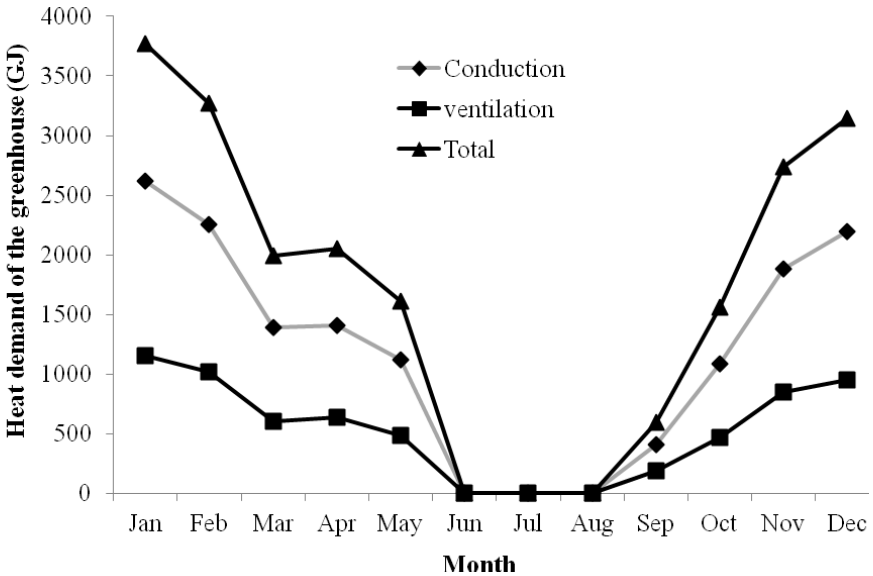

Figure 3-4 Monthly heating demand of the greenhouse based on 2012 weather data (Hamedani, et al. 2014)

Table 3-1 Estimation of special greenhouse operations and greenhouse area (CANSIM database, Statistics Canada 2014)

Specialized greenhouse fruits and vegetables	Total greenhouse operations	735
	Total greenhouse area Glass cover Rigid plastic cover Poly-film cover	1364 ha 42% 1.5% 56.5%
Specialized greenhouse flowers and plants	Total greenhouse operations	1,885
	Total greenhouse area Glass cover Rigid plastic cover Poly-film cover	814 ha 31.5% 5% 63.5%

Table 3-2 Simulated dry matter loss and biomass recovery

	Recovered biomass (Mg)	Dry matter loss (Mg)	Percent biomass loss (%)
Start of the operation	2277.5	0	0
Mowing	1917.5	360	15.8
Raking	1905.8	11.7	2.8
Baling	1840.5	65.3	2.9
On farm transportation	1773.9	66.7	2.4
Loading	1717.8	56.1	0.5
Transportation to storage	1705.3	12.4	3.0
Unloading	1655.2	50.1	2.2
Storing	1605.1	70.5	3.1
Loading	1534.6	51.7	2.3
Transportation to end user	1482.9	11.5	05
Unloading	1471.4	49.7	2.2
Total	1421.7	805.7	35.4

Chapter 4: Delivery of Switchgrass to Mushroom Industry to be Used as Bedding

4.1 Introduction

Mushrooms have become a regular item in groceries and supermarkets internationally. The mushroom industry in Ontario constitutes 57% of the industry in Canada, and the production of mushrooms has ranged from 74000-118000 Mg in the recent decade, generating a value ranging from 154-189 million dollars (Agriculture Agri Food Canada. 2012).

Mushrooms are cultivated in a substrate that is made from a mix of straw, hay, stable bedding, poultry litter, gypsum and water. Because the availability of wheat straw is uncertain at times, alternative growing media such as switchgrass can be considered for the mushroom industry. In Ontario, the price of switchgrass for mushroom bedding was $110-165/Mg in 2012 and 2013 (Engbers et al. 2013). If the mushroom industry embraces switchgrass for bedding, a reliable market can be established for the biomass producers.

Switchgrass is a perennial crop. It grows in Canada as a native crop. There is sufficient marginal land in Ontario to grow this type of biomass. The cost of on-farm operation does not vary significantly but transportation and storage costs can alter the delivered cost of biomass considerably. Hence, it is desirable to choose the most cost efficient combination of storage and transportation methods.

Mushroom Producers Cooperative Inc (MPCI) which is based in Hareley, Ontario since 1990s, is assumed to be the end user of switchgrass in this study. MPCI cooperates with local suppliers and produces a high quality compost. This compost supplies required minerals to grow mushroom. The process of producing compost is associated with odours. MPCI follows the OMAFRA`s standards in order to have odours as less as an ordinary farm practice.

It is assumed that there are five suppliers of switchgrass for MPCI. Five nodes are assumed to be located in New Hamburg, Aylmer, Seaforth, Peterborough, and Burford in Ontario. Bales of switchgrass or wheat straw are delivered from each node to MPCI. Then, bales are kept in MPCI storage before being utilized. The bale trucks arriving at the yard are weighed and unloaded. The biomass is processed gradually to a compost (shown on the corner of figure 4-1) for distribution to member Cooperative mushroom houses.

4.2 Objective

The objective of this chapter is to compare the costs and dry matter losses of delivering switchgrass and wheat straw bales from five nodes and storing in six different storages of: 1) on farmers` field; 2) storage on the gravel pad; 3) storage with tarp; 4) shed without walls; 5) shed with three walls; 6) enclosed shed with ventilation. The IBSAL model is used to simulate four scenarios. Results of these scenarios are compared.

4.3 Methodology

Timing drives decision making in the logistics of biomass supply chain. After harvesting, farmers have limited time to prepare the field for the next crop. Bales from the previous crop must be removed from the field as early as possible. This necessitates storing bales temporarily on the road side next to the farm or at a more centralized location. Short and long term storage must also cope with variations in demand from biomass users. Farmers can use storage to take advantage of the market prices. Storage type affects the dry matter loss and cost directly. The focus of this chapter is studying different storage options for MPCI.

It is assumed that MPCI demand of switchgrass is 750 bales per week or 39000 bales per year. The whole supply is delivered from five different farms. The distances are 10 km from farms around Burford near Harley, 50 km from New Hamburg in the North, 75 km from Aylmer in the Southwest, 100 km from Seaforth in the Northwest, 250 km and Peterborough Northeast (Figure 4-2). The average of the five distances is assumed to be the baseline distance. Bales are transported by trailer trucks each holding 36 bales. The bale density is 160 kg/m^3 and the size of each bale is 3 m x 4 m x 8 m. Mass of each bale is assumed to be 435 kg. Total mass of bale to deliver is 16963 Mg. It is assumed that the bales are stacked 6 bales high. Height of each stack is 5.4 m.

Four scenarios were investigated in this chapter:

1 - Base case scenario

In the base case, storing wheat straw in six storage methods of on farm side, unprotected on the gravel, tarped on the ground, shed with no walls, shed with three walls and enclosed building are investigated. It is assumed that all of the bales are supplied from one node which is 40 km away from MPCI.

2 - Straw Location Scenario

In the second scenario, wheat straw bales are delivered from five nodes of Buford, New Hamburg, Aylmer, Seaforth and Peterborough in Ontario to MPCI. Three storages methods of on farmer`s field, tarped and shed with three walls are compared in this scenario, as well. The effects of storage type and transportation distances are clearly shown in this scenario.

3 - Straw Field to MPCI Scenario

In the third scenario, wheat straw is directly transported to MPCI. It is assumed that there is only one node which is 40 km away and only one storage method of on the field. The cost of storage is assumed to be zero as it is on the farmer`s field. Dry matter loss happened due to spoilage and also physical loss. More bales are required in order to compensate the loss. It is vital to sort the bales and remove those spoiled bales from the system. Sorted and unsorted systems are also compared in the third scenario.

4 - Switchgrass Location Scenario

In the fourth scenario switchgrass is used as biomass. Bales of switchgrass are transported from five nodes of Buford, New Hamburg, Aylmer, Seaforth and Peterborough in Ontario to MPCI. Three storage methods of on the farmer`s field, tarped and shed with three walls are studied. The goal of this scenario is to be compared with the second scenario and show the effect of crop type on the system.

4.3.1 Growing and Harvest

Total farm gate cost is comprises of costs of growing and harvest. It is assumed that for wheat straw the farm gate cost is \$26.39/Mg (IBSAL data base). Samson et al. 2007 showed that the growing and harvest cost of switchgrass is \$40-50/Mg. The average inflation rate is assumed to be 0.02 from 2007 to 2014 in Canada (Bank of Canada, 2013). Then the farm gate cost of switchgrass is calculated to be \$45.5/Mg in 2014.

4.3.2 Transportation

Distance of farm to MPCI varies for each supplier. The average distance of five suppliers is considered as baseline distance. The number of bales per truck is 36. Regardless of crop and storage type, 39000 bales are supposed to be delivered to MPCI annually. The share of each node is 7800 bales in a year. Number of loads per year is calculated to be 217 for each supplier.

It is assumed that the average speed of the truck is 50 km/hr. Therefore, it takes 0.4 hr, 2 hr, 3 hr, 4 hr, and 10 hr to deliver bales from Buford, New Hamburg, Aylmer, Seaforth and Peterborough respectively. It is assumed that the cost of travel per load is \$139.81/hr (IBSAL data base). Hence, cost of travel per load is calculated to be \$55.92, \$279.62, \$419.43, \$559.24, and \$1398.1 respectively for Buford, New Hamburg, Aylmer, Seaforth and Peterborough. Also it is assumed that the cost of loading is \$22.92/hr (IBSAL data base). Cost per load is calculated by adding cost of loading and cost of traveling. Total transportation cost is calculated \$14600, \$63067, \$93360, \$123652, and \$305405 respectively for Buford, New Hamburg, Aylmer, Seaforth and Peterborough.

4.3.3 Storage

A proper configuration can decrease the risk of fire in a large stack of bale. According to the International Fire Code, maximum tonnage of a single stack can be 100 Mg. A fire lane has to be provided in between each stack (ICC, 2003). In this study, fire lane is considered by applying the filling factor.

A filling factor is assumed to be 0.75 for outside storage and 0.9 for inside storage. In outside storage, the temperature of the stack may increase due to direct sunlight. However, because of higher expenses of inside storage, it is more beneficial to have filling factor of 0.9. The various methods of storing biomass are briefly outlined below. Literature review showed that the existing data of cost and dry matter loss has shortcomings. Experiments have been done in various regions with different conditions. It is not argumentative to compare data of different resources with different conditions. Hence, author used the average data of cost and dry matter losses in this study (Table 4-1).

Different storage methods that are used in this study are as followed:

On farmer`s field

Outside and unprotected storage of bales can be considered as an option of storage is intended for a short time period. As bales are stored on the farm side, storage cost is assumed to be $0.0/m^2 (IBSAL data base). Since farmers use their own farm side for storage, this method is always an available option. It is assumed that bales are kept on unprepared ground. High dry matter loss is a disadvantage of this storage method. Dry matter loss of switchgrass bales is assumed to be 50% for switchgrass and 40% for what straw (IBSAL data base).

Unprotected on gravel pad

This option of storage is comparable with on farmer`s field storage method. The only difference is that the bales are kept on the gravel pad. Gravel pad allows for the drainage of water and the bales are not in contact with wet ground to absorb water, resulting in lower dry matter loss and spoilage in the bales. Storage cost was reported to be $0.57/m^2 (IBSAL data base). It is assumed that annual dry matter loss of switchgrass bale is 35%, and 30% for wheat straw while it is stored outside and unprotected on gravel pad (IBSAL data base).

Tarped on the ground

Precipitation is the main cause of bales' spoilage in outside storage. Farmers can use tarp to cover the bales in order to reduce water absorption and hence dry matter loss. Tarps should be checked and cleaned regularly since heavy snow might cause deformation in the bales. Dry matter loss of tarped bales of switchgrass and wheat straw are assumed to be 17% and 15% respectively. Annual storage cost was reported to be $0.67/m^2 (IBSAL data base).

Shed with no walls

To keep biomass for a longer period of time it is important to keep the bales away from precipitation and other elements. One of the most common and least expensive method is a covered flat floor without walls. This is suitable for regions where the precipitation level is relatively high. Due to the cost of infrastructure and maintenance, protected storage methods are more expensive than unprotected storage methods. The cost of storing in a shed with no walls is assumed to be $4.96/m^2. Dry matter loss has been reported to be within 8% for switchgrass and 6% for wheat straw (IBSAL data base).

Under a shed with 3 walls (Barn)

A shed with three walls can protect the biomass from snow or rain especially in windy areas. In this case dry matter loss is lower than outside storage. The advantage of this method vs. completely enclosed building is the ease for handling equipment to get in and out of the storage. It fits best to small to medium size bale storage and handling facilities. The storage cost is assumed to be $5.21/m^2. Dry matter loss of switchgrass is assumed to be is 6% for switchgrass and 5% for wheat straw (IBSAL data base).

Enclosed building with ventilation

In this storage method, mechanical (forced) ventilation rather than natural ventilation is used in an enclosed storage, with an aim to minimize the spoilage of bales and hence dry matter loss due to a lack of adequate ventilation. More efficient air movement is achieved. The storage cost is assumed to be $8.29/m^2. Dry matter loss is assumed to be 3% for switchgrass and 2% for wheat straw. Table A1 in the appendix also summarizes the literature review relevant to bale storage.

4.4 Results and Discussion

The costs are for delivering is equivalent to roughly 750 bales per week for 365 days a year. Four scenarios of base case wheat straw, straw locations, straw field to MPCI, and switchgrass locations are investigated. It is assumed that more than 750 bales are transported to MPCI to offset for dry matter loss.

Figure 4-3 following shows the base case scenario where the balses are sorted for dry matter loss prior to tarnsportation. Figure 4-3 shows that harvest and transport cost are the dominant costs. Storage cost becomes noticeable in protected storage scenarios. The option that includes storage with tarp is the cheapest option and is followed closely with storage under the shed and in enclosed store.

The delivery cost of the base case scenario ranges about $50- 69/Mg. Total mass of bale to be delivered is 16963 Mg in this scenario. The more biomass is lost the more biomass should be harvested in order to compensate the loss. Therefore, mass of biomass to harvest is 28272 Mg, 24233 Mg, 19956 Mg, 18046 Mg, 17856 Mg, 17309 Mg for respectively left on the field, storage on gravel pad, storage with tarp, shed with no walls, shed with three walls, and enclosed building storage methods.

It is assumed that the number of bales are fixed during the process. Dry matter loss causes decrement in the weight of each bale while it is stored. The cost of storage is a function of the area covered by bales and also cost of storage ($/m^2). Total cost of storage is calculated in the base case scenario to be $0/yr, $20980/yr, $20309/yr, $113295/yr, $117707/yr, $181627/yr for respectively left on the field, storage on gravel pad, storage with tarp, shed with no walls, shed with three walls, and enclosed building storage methods.

Transportation is a function of distance. As the distance is equal in this scenario and the truck speed is assumed to be 50 km/hr. Time to deliver (hr) and also number of loads determine the cost of transportation. The total transportation cost is calculated to be $424594/yr,

$363937/yr, $299713/yr, $271017/yr, $268163/yr, $259952/yr for respectively left on the field, storage on gravel pad, storage with tarp, shed with no walls, shed with three walls, and enclosed building storage methods.

Dry matter losses are inevitable in the supply chain of biomass. Physical losses mostly occur during the farm's operation, loading and unloading, as well as transportation. These physical losses may be reduced by more efficient field operation and transportation. Chemical reactions and microbial activities can also cause dry matter loss, and occur mostly during the storage. Rees et al. (1982) suggested that dry matter loss ranged from 18-30%, and most of the losses were due to respiration. Bales that are stored indoor did not have weathered layers.
It is assumed that in delivery of sorted bales, the dry matter loss results in equivalent number of bales that are spoiled. These bad bales are not loaded and transport. For this delivery 39000 good bales each at 423 kg are transported to MPCI.

It is assumed that in delivery of unsorted bales, the dry matter loss results in the loss of weight of each bale. In this case the number of bales that are transported to MPCI are increased to make up for the dry matter loss. The number of bales transported to MPCI is around 65000 when the bales experience a dry mass loss of 40%.

The bar chart shows that delivery cost of transporting sorted bales is more than that transporting unsorted bales but the cost depends upon storage types. The cost items does not include the costs associated with sorting.(Figure 4-4)

In the second scenario, five suppliers and three storage methods are compared. The result of the second scenario is summarized in the figure 4-5. The transport cost for average for 97 km (average of 5 transportation distances) is included in the bar chart. The graph also shows three storage scenarios storage on gravel, tarped bales on gravel, and storage under shed. Transporting from Peterborough is the most expensive ($305405/yr) and from Burford is the cheapest ($14600/yr). The total average costs of delivering from five nodes are $74/Mg, $68/Mg, $70/Mg for the storage on gravel, storage on gravel with pad and protected under shed.

In the third scenario, it is assumed the dry matter loss progressively increases to 0.5 (50% of the original mass) as the bales remain on the farm exposed to weathering elements (rain, snow, wind). The cost of delivering bales directly from farmers' farm to MPCI depended upon the length of time the bales remain on the farm prior to transport.

The assumed distance is 40 km from supplier to MPCI. Bales will lose mass (dry matter loss) as they wait in the field to be taken up. Two options are presented. Transporting sorted bales and transporting un-sorted bales. Sorting is done during loading the truck. We assume no cost associated with sorting. Figure 4-6 shows that for the third scenario the delivery cost of sorted bales incresaes more rapidly than the delivery cost of unsorted bales. The more rapid increase is due to the incresaed number of loads for the sorted bales. Delivered costs for sorted bales are $41/Mg, $46/Mg, $52/Mg, $59/Mg, $69,83/Mg.

In the fourth scenario switchgrass is delivered from five nodes to three storages. The goal of switchgrass scenario was showing the effect of biomass type on the whole system. Figure 4-7 summarizes the detail of the fourth scenario. The more biomass is lost in the storage, the more should be harvested to compensate the loss. Comparison of the storage methods showed that for switchgrass the amount of biomass to harvest is 26097 Mg, 20437 Mg and 18046 Mg respectively for uncovered on gravel, covered with tarp and shed with 3 walls storage methods. However, in the second scenario mass of wheat straw to harvest were 24233 Mg, 19956 Mg and 17856 Mg for unprotected, tarped and shed with 3 walls storage methods. Total harvest cost and also number of bales to be stacked decrease when a more protective storage method is used (Table 4-2).

The amount of dry matter loss after storage is a good measure of bale quality. The dry matter loss of uncovered, tarped and barn storage methods were reported respectively 9134 Mg, 3474 Mg and 1083 Mg for switchgrass and 7270 Mg, 2993 Mg and 893 for wheat straw. As it was expected the dry matter loss of barn storage is the minimum; however barn storage is not the most cost efficient method.

The cost of switchgrass is almost twice as much as the cost of straw because of the extra harvest cost. As the distance increases the difference between the cost of straw and switchgrass increases. Figure 4-8 shows the comparison of switchgrass and wheat straw scenarios.

There are two approaches in choosing a storage method:

1) Investing more in storage and decreasing the dry matter loss

In this approach, the target is to have the least dry matter loss. As the type of storage becomes more protective, the dry mass loss would decrease and thus the number of stacked bales would decrease. For instance, the dry matter loss in the barn storage method is about 1083 Mg for storing switchgrass bale and 893 Mg for storing wheat straw. While this number increases to

9134 Mg and 7270 Mg for storing switchgrass and wheat straw in outside and uncovered storage. The extra demand of biomass causes increment in harvest and transportation costs.

2) Investing less in storage and paying more for harvest and transportation instead

In the second approach, the goal is to have minimum investment in storage. In this order having a temporary storage of outdoor storage might be a good option. In contrast with the first approach, the less protective and cheaper storage method is preferred. This approach leads to more harvest and also more bales to be delivered.

Both of the abovementioned approaches are investigated in the four scenarios. Results showed for both switchgrass and wheat straw harvest cost affects the total cost significantly. The most profitable method for switchgrass is storage under the shed with three walls ($90.8/Mg). Also the most cost efficient method of storing wheat straw is tarped method ($67.6/Mg). Unit delivered costs for both of the crops are summarized in Table 4.3.

Unit delivered cost shows that the best scenario varies based on the crop type. Comparison of the unit costs shows that using switchgrass as biomass is more expensive than wheat straw. Switchgrass cost of growing is higher than wheat straw. As straw is the leftover of wheat, the growing cost of straw is shared with wheat. However, switchgrass is not a bi-products and is harvested to be used just a purpose grown biomass.

Comparison of tarped and uncovered methods showed that $ 0.1/m^2 additional investment in storage method can save 18% switchgrass and 15% what straw. Investment of $4.54/m^2 is required to upgrade tarp method to barn storage method. This upgrade can save 11% switchgrass and 10% wheat straw.

4.5 Conclusions

In this chapter the IBSAL model was used to compare four scenarios of storing switchgrass and wheat straw in Ontario. These scenarios included: 1) base case, 2) straw location, 3) straw field to MPCI, 4) switchgrass location.

The farm gate cost is calculated by adding growing cost to harvest cost. Farm gate cost of switchgrass is more than wheat straw due to a higher growing cost. The growing cost of wheat straw is shared with wheat. For switchgrass farm gate cost is reported to be about $45.5 and for wheat straw the farm gate cost is reported to be about $26.3. Decreasing the growing cost of switchgrass might become possible by finding some other usages for it in future.

Average costs of transportation in the second and fourth scenario, are both reported about $600083, regardless of the type of storage. As it was expected for those suppliers which are closer to MPCI transportation is less expensive. Transportation cost from Burford, New Hamburg, Aylmer, Seaforth, and Peterborough is respectively $14600, $63067, $93360, $123652, $305405. Therefore, the total cost of transportation does not vary case by case.

Cost analysis which included total farm gate cost (harvesting), total transport cost and total cost of storage suggests the most cost efficient method to be “covered with tarp” storage for wheat straw and “shed with three walls” storage method for switchgrass. For switchgrass, the total cost per unit were reported to be roughly $106.7/Mg, $91.4/Mg, and $90.8/Mg for respectively uncovered, covered with tarp, and barn storage methods. These numbers came to about $74.3/Mg, $67.6/Mg and $70.1/Mg for wheat straw. Shed with three walls storage method is recommended for switchgrass and tarp method is recommended for wheat straw.

Dry matter loss is one of the challenges in the biomass and bioenergy industry. The best supply chain scenario might be chosen based on the total cost and total dry matter loss. The dry matter loss of each storage methods was investigated in this study. For switchgrass dry matter loss reported to be 9134 Mg, 3474 Mg, and 1083 Mg while it is stored respectively in uncovered, tarped and barn storage. For wheat straw, the dry matter loss is reported to be 7270 Mg, 2993 Mg and 893 Mg while it is stored in uncovered, tarped and barn storage. Dry matter loss of switchgrass is more than what straw. It has been concluded that for wheat straw showed to be more profitable biomass.

Figure 4-1The MPCI (Mushroom Producers Cooperative Inc. processing yard near Harley, Ontario.

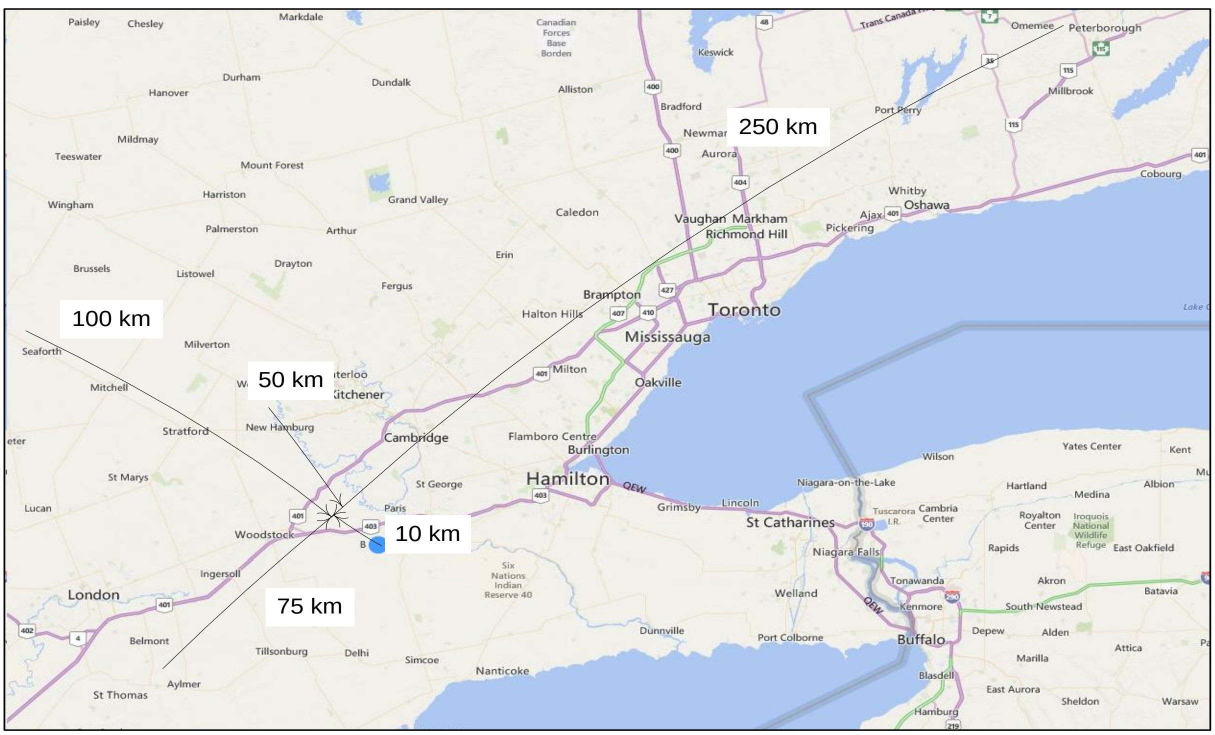

Figure 4-2 A section of map of Ontario showing five scenarios transporting straw and switchgrass bales to the central processing unit at MPCI in Harley Ontario.

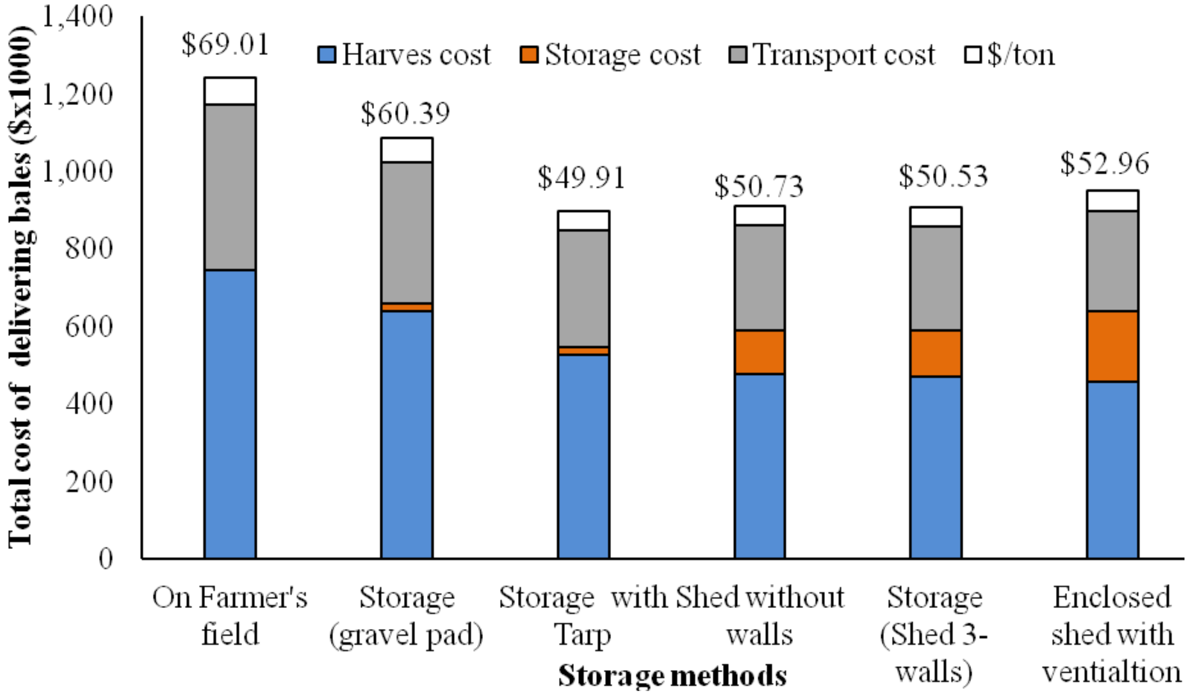

Figure 4-3 Base case scenarios for harvest, storage, and delivering of straw for 40 km transport to MPCI. (Scenario 1)

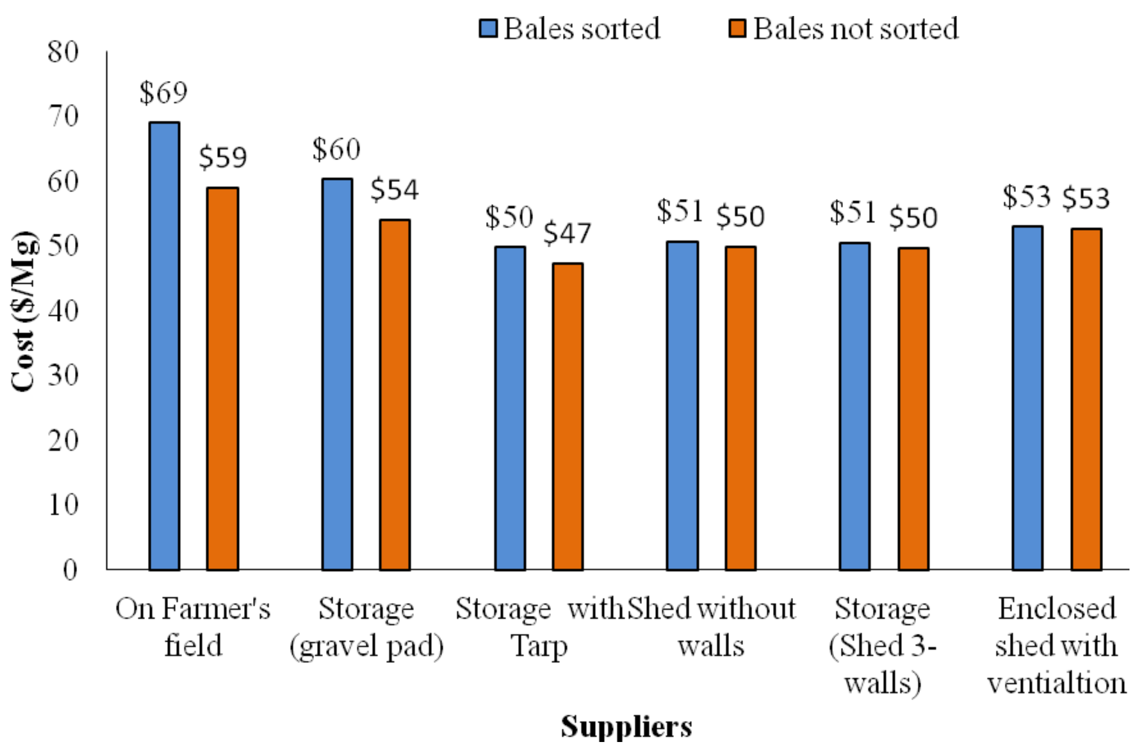

Figure 4-4 Delivery cost of bales – sorted and unsorted straw (Scenario 1)

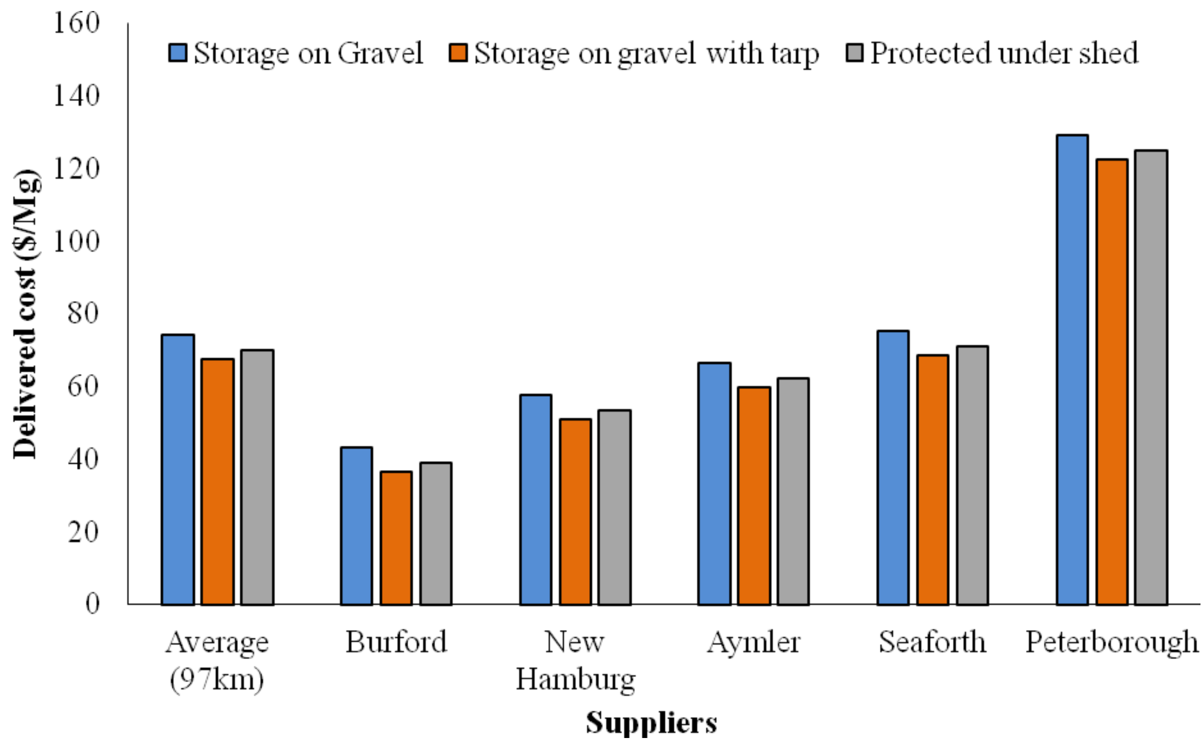

Figure 4-5 Delivered cost of straw bales to MPCI from 5 locations ranging from 10 km Burford to 250 km Peterborough (Scenario 2).

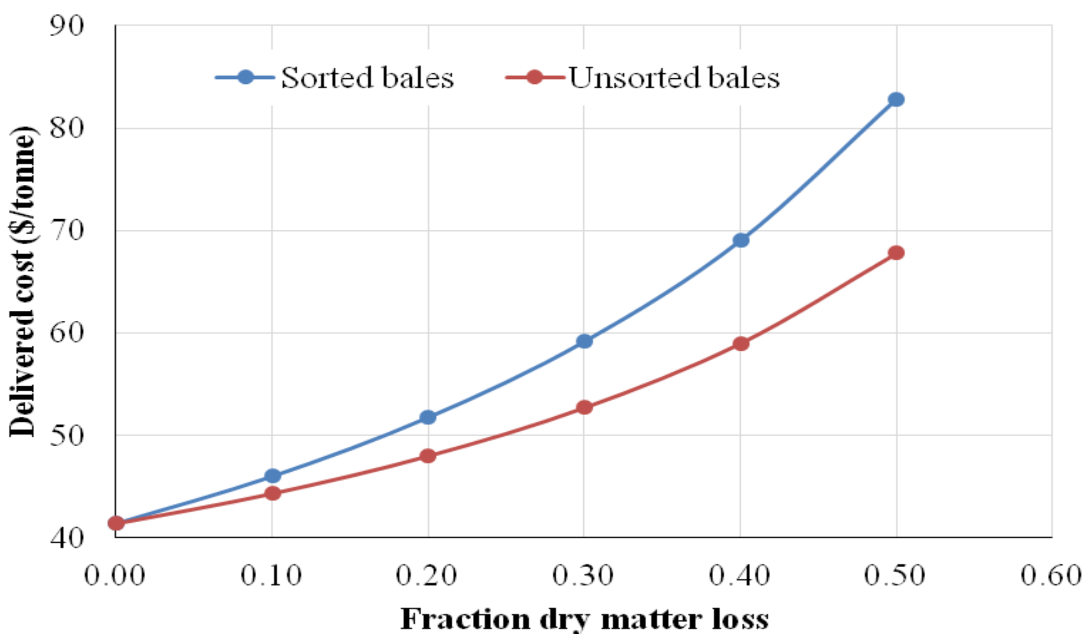

Figure 4-6 Delivered cost of straw bales to MPCI when bales are transported directly from field to MPCI processing site (Scenario 3)

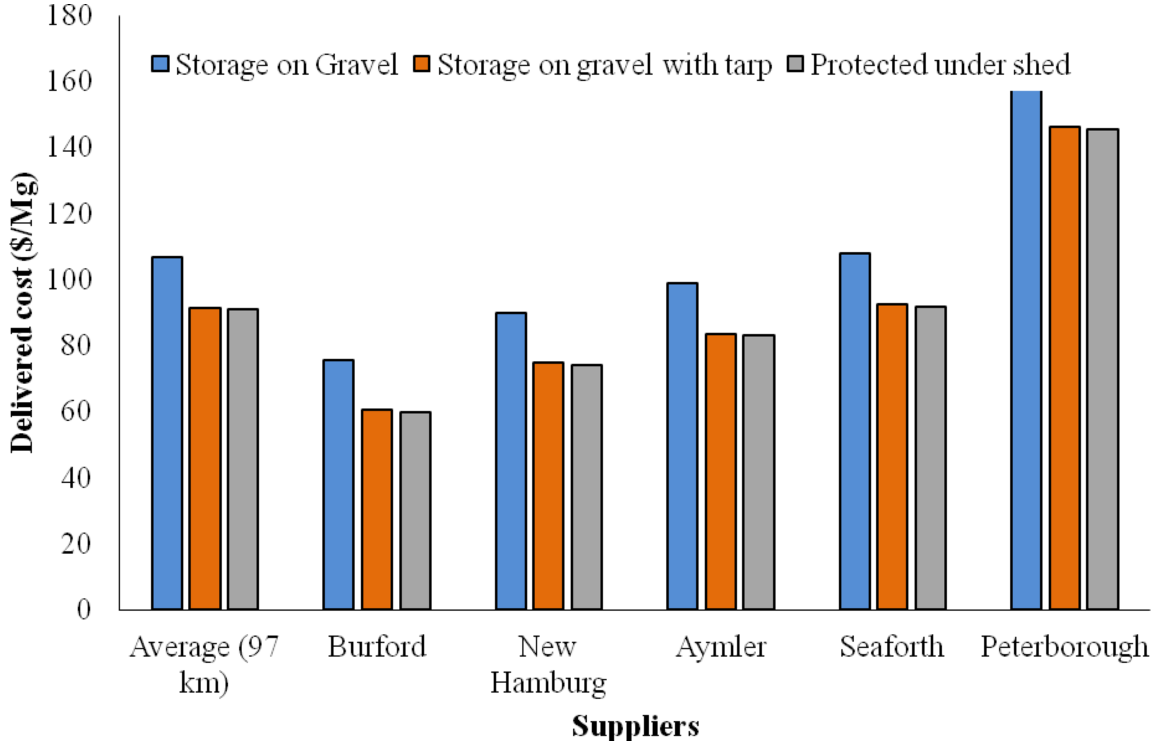

Figure 4-7 Delivered cost of swtichgrass bales to MPCI from 5 locations ranging from 10 km Burford to 250 km Peterborough. (Scenario 4)

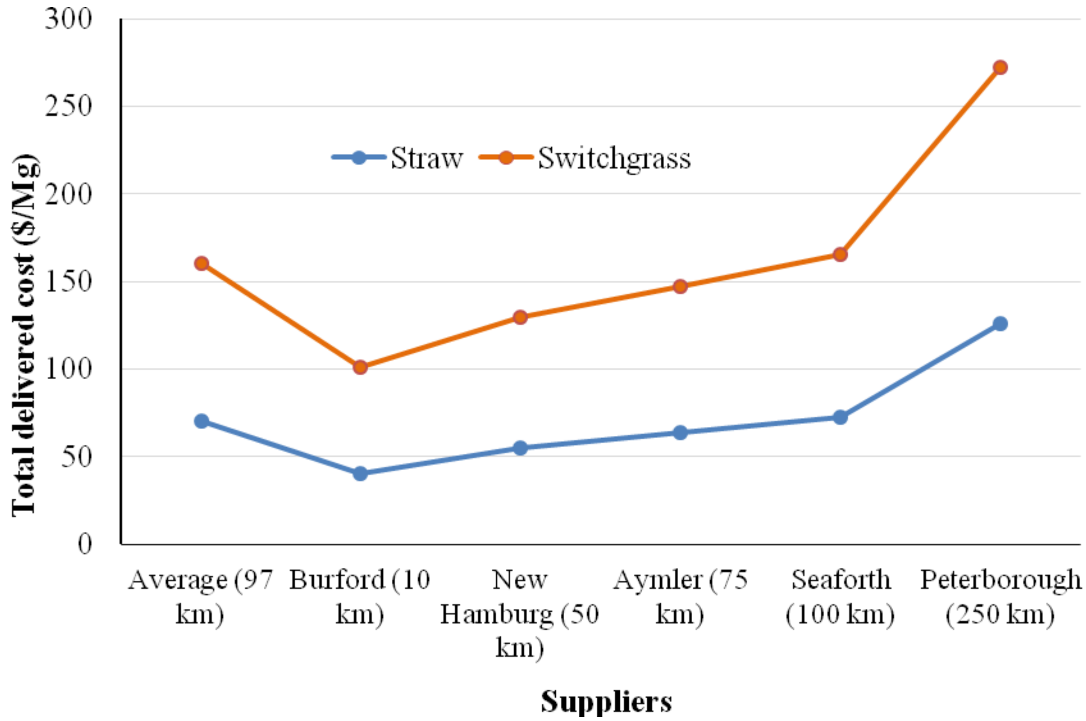

Figure 4-8 The cost of delivery of straw and switchgrass as a function of distance

Table 4-1 Assumptions for IBSAL simulation of harvesting storing and transporting square bales of straw and switchgrass from farmers' fields to MPCI

Biomass crops	Switchgrass vs. Wheat straw
Harvest	Bale squares transport and stack in storage – increased harvested quantities to make up for the dry matter loss
Harvest cost	Straw \$26.39/dry tonne, Switchgrass \$45.52/dry tonne
Bale type	Square 3x4x8, 435 kg
Storage types and costs (fixed annual cost)	No storage direct from farmer's field (0 \$/m^2), Outdoor no protection (0.57 \$/m^2)), Outdoor with tarp (0.67 \$/m^2), Shed no walls (4.96 \$/m^2), Open front shed (5.21 \$/m^2)), Enclosed building (8.29 \$/m^2). The bales are stacked 6 bales high in storage.
Dry matter loss Switchgrass	No storage direct from farmer's field (0.50), Outdoor no protection (0.35), Outdoor with tarp (0.17), Shed no walls (0.08), Open front shed (0.06), Enclosed building (0.03). The bales are stacked 6 bales high in storage.
Dry matter loss Wheat straw	No storage direct from farmer's field (0.40), Outdoor no protection (0.30), Outdoor with tarp (0.15), Shed no walls (0.06), Open front shed (0.05), Enclosed building (0.02). The bales are stacked 6 bales high in storage.
Transport distance (Biomass share)	Truck trailer 36 bales per truck, 97 km (base case 100%)), 10 km Burford (20%), 50 km New Hamburg (20%), 75 km Aylmer (20%), 100 km Seaforth (20%), 250 km Peterborough (20%)
Transport cost	Truck & trailer cost \$139.81per hour of operation (fixed + operating cost) and \$11.46 cost per loading (Source IBSAL data base)
Delivery	750 bale per week for 52 weeks
Bale quality selection	Transporting extra number of bales with lower density to offset for reduced dry matter vs. transporting bales with regular density rejecting bales with dry matter loss.

Table 4-2 List of harvest parameters – mass of biomass to harvest, number of bales to be stacked, total cost of harvest (scenarios 2 &4)

Parameters	On the ground un protected – SG[1]	On the ground unprotected – WS[2]	Tarped on the ground - SG	Tarped on the ground - WS	Barn – shed with 3 walls - SG	Barn – shed with 3 walls – WS
Mass of biomass to harvest, Mg	26097	24233	20437	19956	18046	17856
Number of bales to be stacked	60001	55715	46988	45883	41490	41053
Total cost of harvest, ($)	1187927	639502	930304	526649	821439	471212

1- Switchgrass. 2- Wheat straw

Table 4-3 Unit delivered cost ($/Mg)

	Total unit delivered cost ($/Mg)
Unprotected on the ground – SG	106.7
Unprotected on the ground – WS	74.3
Tarped on the ground – SG	91.4
Tarped on the ground – WS	67.6
Barn – shed with 3 walls – SG	90.8
Barn – shed with 3 walls – WS	70.1

Chapter 5: Conclusion and Future Work

5.1 Conclusions

The IBSAL model simulates the physical flow of biomass from field to biorefinery. The model accounts for variable yield, moisture content, and the effects of weather elements on the progress of biomass collection and transport operations. The cost calculations are based upon an accurate account of all factors that affect the final delivered cost. At present the output data depends upon the existing information on bulk density, moisture relations, and biochemical reactions during storage and transport.

The major goal of having five scenarios is comparing the options of transportation methods. However, the feasibility of having the central storage, side farm storage and using round or square baler is investigated, as well.

Five scenarios in the OPG case were studied. The output showed that the barge and railroad scenarios are not as cost efficient as other scenarios unless the distance is more than 150 km. Direct scenario is reported as the cheapest scenario with minimum dry matter loss. Depend on the size of the facility, timeline of delivering material, and the specifications of the end user central storage could be considered as an alternative. Central storage is a value added item in the supply chain which saves more biomass in the supply chain. It is reasonable to invest in a central storage and make a reliable, constant flow of biomass for the end user.

Dry matter loss occurs in each item of the biomass supply chain. Usually matching supply and demand of biomass is a big challenge for both farmer and end user. In the greenhouse case, calculating the heat demand of a greenhouse and simulating the supply chain of biomass helped us in matching the supply and demand of switchgrass. The results showed that more suppliers are required in order to satisfy the end users. Other solution could be decreasing the dry matter loss in each step of the supply chain. The procedure of this example can be extended to bigger facilities such as hospitals, prisons, and schools.

In the last case, delivering switchgrass to mushroom industry was studied. In contrast with abovementioned cased; switchgrass was not considered as bioenergy. Switchgrass can be used as a proper substitute of corn stover in bedding for mushroom industries. Four different scenarios were investigated in terms of dry matter loss, and cost. Results showed that shed with three walls and tarp storage methods are the most efficient for switchgrass and corn stover respectively.

5.2 Future Work

5.2.1 Input Data

The Integrated Biomass Supply Analysis & Logistics model (IBSAL) is operational, but requires field data in order to calculate the costs and other outputs accurately.

Data on physical properties of biomass - bulk density varies with biomass type, particle size and moisture content. Bulk density has the largest effect on predicting the performance of transport equipment and storage structures. Rigorous data need to be established for straw and stover and other residues considered for analysis.

Data on machinery performance – The length and number of times a machine is allocated to a process depends upon the speed, width, field efficiency and work interruptions due to repairs and machine preparation. These data, including power and fuel use by the equipment have to be collected in the field and used in the model to calculate working rates more accurately.

From the reviewed literature, author comes to this conclusion that the existing data of corn stover production in Ontario has several shortcomings. Oo et al. 2012b did an estimation of corn stover production. However, a real data of the region could be beneficial.

5.2.2 Modifying the Model

The model structure will be modified into a series of independent modules: input modules, operational modules, and output modules. EXTEND SIM can be fully integrated with EXCEL and EXCEL data base. A library of modules, each module to represent a unit operation (e.g. shredding, baling, forage harvesting, etc.), should be developed. A modeler will be able to pick and drop modules easily and efficiently into a simulation program.

The model will be validated by constructing the existing biomass supply systems and verifying the output against inputs. Future work will apply the model to investigate the supply chain of torrefied and/ or pelletized material.
It will be beneficial to take the carbon emission and energy consumption of the barge and railroad scenarios into account in the future works.

5.2.3 Investigation of Other Agricultural Biomass in Ontario

The focus of this research was on switchgrass and corn stover as purpose grown biomass. By choosing other agricultural biomass such as wheat straw, miscanthus, poplar and willow a valuable comparison can be done. Also using IBSAL model in other provinces of Canada is recommended by author. In British Columbia, for instance, there are farmers who grow switchgrass and sell it to different end users. Analyzing the supply chain of agricultural biomass and comparing it with the Ontario model is also recommended.

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Appendices

Appendix A calculation heat demand of OPG

Table A-1 Input data, assumptions and energy demand of OPG

Corn stover heat value (GJ/Mg)	17.8
Corn stover moisture content at harvest time (W.B)	30%
Generating Capacity (GW)	0.5
Heat Rate (GJ/GWhr)	10,100
Capacity factor %	5
Co fire	100%
Working day	365
Working hours per day (hr)	24
Working hours per year (hr)	8,760
Energy Demand (GJ)	2211900

$$ED = GC \times HR \times CAF \times COF \times RH \qquad 5\text{-}1)$$

Where ED is energy demand (GJ), GC is generating capacity (GW), HR is heat rate (GJ/GWhr), CAF is capacity factor, COF is cofire and RH is running hours (hr).

Appendix B output of mushroom case, switchgrass

Base case wheat straw	**Storage (gravel pad)**	**Storage with Tarp**	**Storage (Shed 3-walls)**
Fraction of supply	**1**	**1**	**1**
Biomass Loss (percent)	0.35	0.17	0.06
Cost of storage building ($/square m-year)	0.57	0.67	5.21
Bale density (kg/m3)	160	160	160
Bale volume (3x4x8) (m3)	2.7	2.7	2.7
Single bale height (m)	0.91	0.91	0.91
Mass of each bale (kg)	434.9	434.9	434.9
Number of bales delivered per week	750	750	750
Number of weeks	52	52	52
Total number of bales to be delivered	39000	39000	39000
Total mass of bales to be delivered (Mg)	16963	16963	16963
Harvest			
Cost of harvest ($/dry tonne)	45.52	45.52	45.52
Mass of biomass to harvest (Mg)	26097	20437	18046
Number of bales to be stacked	60001	46988	41490
Total cost of harvest ($)	1187927	930304	821439
Storage			
Number of bales stacked on 4' x 8 ' feet side	6	6	6
Height of each stack (m)	5.4864	5.4864	5.4864
Total volume of bales (m3)	163108	127733	112787
Net area storage under bales (m2)	29729	23282	20558
Fill factor	0.75	0.75	0.90
Gross area (m2)	39639	31042	22842
Cost of storage area per square m2 ($/m2)	0.57	0.67	5.21
Total cost of storage ($/yr)	22594	20798	119006
Transportation			
Number of bales per truck	36	36	36
Total number of bales	39000	39000	39000
Number of loads	1083	1083	1083
Distance to travel (km)	97	97	97
Average speed (km/hr)	50	50	50
Hours per load	3.88	3.88	3.88
Cost of travel per load (139.81/hr)	542.46	542.46	542.46
Cost of loading per load (30 minutes)	11.460	11.460	11.460

Appendix B output of mushroom case, switchgrass

Base case wheat straw	**Storage (gravel pad)**	**Storage with Tarp**	**Storage (Shed 3-walls)**
Cost per load	554	554	554
Total transport cost	600083	600083	600083
Summary cost			
Harves cost	1187927	930304	821439
Storage cost	22594	20798	119006
Transport cost	600083	600083	600083
Sum of delievred cost	1810604	1551185	1540527
$/ton	106.74	91.45	90.82
dry matter loss to compensate	9134	3474	1083
Harves cost	1188	930	821
Storage cost	23	21	119
Transport cost	600	600	600
$/ton	106.74	91.45	90.82

Appendix C Outputs of mushroom case wheat straw

Base case wheat straw	**Storage (gravel pad)**	**Storage with Tarp**	**Storage (Shed 3-walls)**
General			
Fraction of supply	**1**	**1**	**1**
Biomass Loss (percent)	0.30	0.15	0.05
Cost of storage building ($/square m-year)	0.57	0.67	5.21
Bale density (kg/m3)	160	160	160
Bale volume (3x4x8) (m3)	2.7	2.7	2.7
Single bale height (m)	0.91	0.91	0.91
Mass of each bale (kg)	434.9	434.9	434.9
Number of bales delivered per week	750	750	750
Number of weeks	52	52	52
Total number of bales to be delivered	39000	39000	39000
Total mass of bales to be delivered (Mg)	16963	16963	16963
Harvest			
Cost of harvest ($/dry tonne)	26.39	26.39	26.39
Mass of biomass to harvest (Mg)	24233	19956	17856
Number of bales to be stacked	55715	45883	41053
Total cost of harvest ($)	639502	526649	471212
Storage			
Number of bales stacked on 4' x 8 ' feet side	6	6	6
Height of each stack (m)	5.4864	5.4864	5.4864
Total volume of bales (m3)	151457	124729	111599
Net area storage under bales (m2)	27606	22734	20341
Fill factor	0.75	0.75	0.90
Gross area (m2)	36808	30312	22601
Cost of storage area per square m2 ($/m2)	0.57	0.67	5.21
Total cost of storage ($/yr)	20980	20309	117752
Transportation			
Number of bales per truck	36	36	36
Total number of bales	39000	39000	39000
Number of loads	1083	1083	1083
Distance to travel (km)	97	97	97

Appendix C Outputs of mushroom case wheat straw

Base case wheat straw	**Storage (gravel pad)**	**Storage with Tarp**	**Storage (Shed 3-walls)**
Average speed (km/hr)	50	50	50
Hours per load	3.88	3.88	3.88
Cost of travel per load (139.81/hr)	542.46	542.46	542.46
Cost of loading per load (30 minutes)	11.460	11.460	11.460
Cost per load	554	554	554
Total transport cost	600083	600083	600083
Summary cost			
Harves cost	639502	526649	471212
Storage cost	20980	20309	117752
Transport cost	600083	600083	600083
Sum of delievred cost	1260566	1147041	1189047
$/ton	74.31	67.62	70.10
dry matte loss to compensate	7270	2993	893
Harves cost	640	527	471
Storage cost	21	20	118
Transport cost	600	600	600
$/ton	74.31	67.62	70.10

Appendix D (Communication with Jake DeBruyn) 2014-09-16

Mushroom Producers Cooperative Inc. (MPCI)
Factors to be considered:

- Base scenario: wheat straw hauling from uncovered side field storage.
- Let's assume five nodes for the hay suppliers:
  - New Hamburg ON (50 km)
  - Aylmer ON (75 km)
  - Seaforth (100 km)
  - Peterborough (250 km)
  - Plus a local node, Burford (10 km) for local farmers
  - Assume 20% of hay comes from each location.
  - Assign a rotating weekly distribution of material from each location
  - Although reality is there's not a central depot, simply assume material all comes from one spot.
- Alternative 1: Cover straw with tarps at side field storage. Analyse increased labour cost, decreased damage, with D.M loss as a proxy for damage. Damage in the form of wet/rotten bales results in lower quality composting.
- Alternative 2: Move the straw from the field directly to flatbeds, unload, store in covered storage building. Again, use improvement in D.M. retention as a proxy for reduced damage.
  - Assume hauling to storage is average 20 km from the field (since this is a large quantity of biomass). Of if you want to be really fancy, use BIMAT to determine the crop rotation in each area, figure out the local acreage of wheat, then figure that the straw broker collects 25% of local wheat straw, and determine what the circumference and related average hauling distance would be. That's more of an academic exercise, but a good one if time permits.
- For baseline and 2 alternatives analyse dry matter retained/ lost, operational and labour and storage cost differences.
- Conclusion will be analysis of increased cost associated with better bail quality.
- Alternative 3: Forget straw – it's too variable and unpredictable. Keeping as much as possible everything else the same, let's swap wheat straw for switchgrass.
  - Rationale: unlike wheat which is rotational, subject to a farmer's choice whether it is grown, once SG is planted the farmer is committed. So MPCI would have dedicated contracts. Since it's a dedicated crop, it comes from a relatively smaller collection zone (i.e. wheat is part of a 3-crop rotation, corn/soybeans/wheat, with only 1/3 of the acres in wheat at any one time, where-as with SG there's no rotation, 100% of acres are in SG). So the 20 km (or BIMAT value) hauling to storage value should be lower. Re-do the calculation of distance to storage using 100% dedicated SG acres (i.e. try to keep everything else the same).
  - All in-building stored (highest quality).
  - What's the increase cost to achieve this high confidence, high quality SG model, in comparison to the high quality wheat straw example?

Biomass collection details

- Weekly delivery of wheat straw bales to MPCI from various sources
- 700 – 800 bales per year
- Metric tonnes
- 380 tonnes/week to 400 tonnes/week
- Buys 20,000 tonnes/year
- Winter sometimes uses less because more horse manure received, 30-40 tonnes less per week
- Wheat straw
- Bale weight
    - 3 X 4 X 8 450 – 500 kg.
    - 4 X 4 X8 450-650 kg.
    - Standard bales, not high density bales.
- Quality varies depending on weather, time of year, tightness of the bale.
- Some bales come from covered storage, some in barns, most of it is stored outside at the farms where it is produced. Mostly uncovered storage. For IBSAL scenario, will assume 100% uncovered (baseline), 100% field tarped (Alt 1), 100% barn storage (Alt 2).
- Top bales versus bottom bales is a big difference. Sometimes he doesn't even accept the top ones because so rotted from rainfall, snow, and exposure
- Suppliers collect from widely dispersed locations. The suppliers also do farming themselves. Joe thinks that bales come from as far as from Windsor (260 km), New Liskeard (600 km), Lion's Head (270 km). Plus MPCI buy from local farmers, 100 bales here or there.
- Generally 44-46 bales per truck (4X 3X8 big bales). 26 if big 4X4 bales.
- MPCI uses a JCB telehandler 541. Only use for it bale unloading and bale moving on-site. But basically that keeps the unit busy. Bales are pre-wet in bunkers prior to composting. Machine is constantly busy. Also have attachment for the big wheel loaders onsite if need a back-up. But generally since bales are delivered according to a schedule, there's no more than 2 trucks at a time on-site.

Other background details:

This is a huge operation! The mushroom sector is one of the largest biomass users in Ontario, and MPCI is a large centralized composting facility that produces Mushroom Substrate (i.e. compost) for a number of mushroom producers. Their primary ingredients are straw, chicken manure, horse manure, gypsum, and water. They receive several truck loads per day of inputs, mix them on a big concrete yard, the load them into huge industrial composters. After a few days the material is pulled out with a loader, turned, recomposted. Then it is pulled out and put into a second high stage composter to finish. The finished compost or mushroom substrate is then sent to mushroom farms where actual mushroom production occurs. After mushrooms are harvested the end product compost is called "spent mushroom substrate" or SMS, which is then used as a crop nutrient.

The site is located in Harley Ontario, southwest of Burford Ontario. On the map below it's located on Middle Townline Rd, just south of Fairfield Rd, just south of the "25" sign, the white blob on the right hand side of the road.

Appendix E Summary of the literature review, bale storage

Crop	type of bale	storage treatment	period of storage	Initial Moisture content (% wb)	Final Moisture content	dry matter loss (%)	cost ($)	reference
reed canarygrass	sisal twine - large round bale	outdoor	293 (d)	NA	NA	14.5	NA	1
reed canarygrass	plastic twine	outdoor	293 (d)	NA	NA	8.1	NA	1
reed canarygrass	net wrap	outdoor	293 (d)	NA	NA	6.5	NA	1
reed canarygrass	breathable film	outdoor	293 (d)	NA	NA	5.2	NA	1
reed canarygrass	wrapped plastic film tube and ensiled	outdoor	293 (d)	NA	NA	1.1	NA	1
reed canarygrass	IN	Indoor	293 (d)	NA	NA	1.6	NA	1
reed canarygrass	wrapped plastic film tube and ensiled	Indoor	293 (d)	NA	NA	0.8	NA	1
Switchgrass	sisal twine - large round bale	outdoor	293 (d)	NA	NA	15.4	NA	1
Switchgrass	plastic twine	outdoor	293 (d)	NA	NA	9.3	NA	1
Switchgrass	net wrap	outdoor	293 (d)	NA	NA	9	NA	1
Switchgrass	breathable film	outdoor	293 (d)	NA	NA	5.4	NA	1
Switchgrass	wrapped plastic film tube and ensiled	outdoor	293 (d)	NA	NA	5.7	NA	1
Switchgrass	IN	Indoor	293 (d)	NA	NA	4.9	NA	1
Switchgrass	wrapped plastic film tube and ensiled	Indoor	293 (d)	NA	NA	2	NA	1

Appendix E Summary of the literature review, bale storage

Crop	type of bale	storage treatment	period of storage	Initial Moisture content (% wb)	Final Moisture content	dry matter loss (%)	cost ($)	reference
alfalfa	mid size rectangular bale	stacked	30 (d)	16.8	10.8	5	NA	2
alfalfa	mid size rectangular bale	stacked	30 (d)	19.1	10.8	4.4	NA	2
alfalfa	mid size rectangular bale	stacked	30 (d)	21.2	10.8	8.2	NA	2
alfalfa	mid size rectangular bale	individual	30 (d)	16.9	11.7	4.4	NA	2
alfalfa	mid size rectangular bale	individual	30 (d)	18.7	11.3	3.6	NA	2
alfalfa	mid size rectangular bale	individual	30 (d)	21.2	12.6	15.7	NA	2
alfalfa	small size rectangular bale	stacked	30 (d)	15.5	12.5	0.6	NA	2
alfalfa	small size rectangular bale	stacked	30 (d)	17	15	1.4	NA	2
alfalfa	small size rectangular bale	stacked	30 (d)	21.2	12.4	0.1	NA	2
alfalfa	small size rectangular bale	individual	30 (d)	15.5	12	3.7	NA	2
alfalfa	small size rectangular bale	individual	30 (d)	17	11.7	1.5	NA	2
alfalfa	small size rectangular bale	individual	30 (d)	21.2	12.3	0.4	NA	2
alfalfa	round bale	inside	6- 9 months	NA	NA	6	NA	3
alfalfa	round bale	outside	6- 9 months	NA	NA	16.3	NA	3
Switchgrass	round bale	outside	6 month	NA	NA	13	NA	4
alfalfa	round bale	inside	7 months	NA	NA	2.2	NA	5

Appendix E Summary of the literature review, bale storage

Crop	type of bale	storage treatment	period of storage	Initial Moisture content (% wb)	Final Moisture content	dry matter loss (%)	cost ($)	reference
alfalfa	round bale	tarped on pallet	7 months	NA	NA	1.3	NA	5
alfalfa	round bale	outside	7 months	NA	NA	5.1	NA	5
Bermuda grass	round bale	outside	8 months	NA	NA	14.1	NA	6
Bermuda grass	round bale	tarped on pallet	8 months	NA	NA	2.6	NA	6
Bermuda grass	round bale	inside	8 months	NA	NA	3.4	NA	6
alfalfa	round bale	inside	5 months	NA	NA	2	NA	7
alfalfa	round bale	tarped on pallet	5 months	NA	NA	7.5	NA	7
alfalfa	round bale	outside	5 months	NA	NA	9.9	NA	7
Switchgrass	round bale	inside	6 month	NA	10.24	0.7	NA	8
Switchgrass	round bale	tarped on pallet	6 month	NA	22.4	0.37	NA	8
Switchgrass	round bale	tarped on gravel	6 month	NA	8.82	1.58	NA	8
Switchgrass	round bale	untarped on gravel	6 month	NA	17.98	17.27	NA	8
Switchgrass	round bale	tarped on ground	6 month	NA	8.38	1.41	NA	8
Switchgrass	round bale	untarped on ground	6 month	NA	19.13	17.34	NA	8

Appendix E Summary of the literature review, bale storage

Crop	type of bale	storage treatment	period of storage	Initial Moisture content (% wb)	Final Moisture content	dry matter loss (%)	cost ($)	reference
Switchgrass	round bale	untarped on pallet	6 month	NA	22.14	15.38	NA	8
alfalfa	twine	inside	26 weeks	15.2	15.4	67	NA	9
alfalfa	plastic	outside	26 weeks	NA	NA	NA	NA	9
alfalfa	net	outside	26 weeks	NA	NA	NA	NA	9
alfalfa	twine	outside	26 weeks	NA	NA	NA	NA	9
miscanthus	stack with tarp	outdoor	9 months	NA	11.4		NA	10
miscanthus	stack without tarp	outdoor	9 months	NA	11.1		NA	10
wheat hay	row with no cover	directly on the ground	10 months	22.8	14.5	19.2	NA	11
wheat hay	row with no cover	on pallets	10 months	23.1	13.6	13.8	NA	11
wheat hay	row with black polyethylene cover	on pallets	10 months	23.5	10.2	6.4	NA	11
wheat hay	individual bale with no cover	directly on the ground	10 months	22.5	12.7	16	NA	11
wheat hay	individual bale space 0.3 m - no cover	directly on the ground	10 months	23.3	11.6	12.9	NA	11

Appendix E Summary of the literature review, bale storage

Crop	type of bale	storage treatment	period of storage	Initial Moisture content (% wb)	Final Moisture content	dry matter loss (%)	cost ($)	reference
wheat hay	barn	inside	10 months	23.7	11.6	7.9	NA	11
alfalfa	round bale	inside	8 months	NA	NA	4.6	NA	12
alfalfa	round bale	outside - no cover - on the ground	8 months	NA	NA	10.9	NA	12
alfalfa	round bale	outside - no cover - elevated	8 months	NA	NA	7.5	NA	12
alfalfa	round bale	outside - covered - on ground	8 months	NA	NA	5.2	NA	12
alfalfa	round bale	outside - covered - elevated	8 months	NA	NA	7.5	NA	12
alfalfa	rectangular bale	inside	8 months	NA	NA	5.1	NA	12
Reed canarygrass	round bale	outside - sisal twine	11 months	11.3	21.7	14.9	NA	13
Reed canarygrass	round bale	outside - plastic twine	11 months	11.3	23.2	7.5	NA	13
Reed canarygrass	round bale	outside - net wrap	11 months	11.6	20.5	7.7	NA	13
Reed canarygrass	round bale	inside	11 months	11.6	16.6	2.6	NA	13

Appendix E Summary of the literature review, bale storage

Crop	type of bale	storage treatment	period of storage	Initial Moisture content (% wb)	Final Moisture content	dry matter loss (%)	cost ($)	reference
Reed canarygrass	film wrap tube	outside	11 months	33.9	34.3	0.3	NA	13
Switchgrass	film wrap tube	outside	11 months	49	49.5	1.9	NA	13
alfalfa	round bale	outside - exposed - on the ground	8 months	11.5	18.3	54.1	NA	14
alfalfa	round bale	outside - exposed - on pallets	8 months	11.5	17.7	36.8	NA	14
alfalfa	round bale	outside - covered - on ground	8 months	11.1	11	26.9	NA	14
alfalfa	round bale	outside - covered - on pallets	8 months	11	10.6	8.1	NA	14
alfalfa	round bale	barn	8 months	11	11.2	8	NA	14
sorghum	round bale	inside	6 months	11	NA	4.67	NA	15
sorghum	round bale	on ground	6 months	11	NA	8.2	NA	15
sorghum	round bale	on pallet	6 months	11	NA	6.04	NA	15
sorghum	round bale	on pallet - covered with tarp	6 months	11	NA	6.34	NA	15
sorghum	square bale	inside	6 months	11	NA	5.56	NA	15
sorghum	square bale	on ground	6 months	11	NA	12.6	NA	15
sorghum	square bale	on pallet	6 months	11	NA	5.73	NA	15
sorghum	square bale	on pallet - covered with tarp	6 months	11	NA	5.73	NA	15

Appendix E Summary of the literature review, bale storage

Crop	type of bale	storage treatment	period of storage	Initial Moisture content (% wb)	Final Moisture content	dry matter loss (%)	cost ($)	reference
bermudagrass	round bale	no cover - exposed - on the ground	8 months	NA	22.5	7	NA	16
bermudagrass	round bale	no cover - exposed - on the pallet	8 months	NA	21.4	10	NA	16
bermudagrass	round bale	black polyethylene cover - on pallet	8 months	NA	10.1	2.6	NA	16
bermudagrass	round bale	individual - exposed - on the ground	8 months	NA	39.1	12	NA	16
bermudagrass	round bale	individual - exposed - stored on posts	8 months	NA	30.4	12.8	NA	16
bermudagrass	round bale	barn	8 months	NA	11	3.4	NA	16
Hay	round bale	outdoor on crushed stone	NA	NA	NA	NA	1.3	17
Hay	round bale	stretch wrap - shell only	NA	NA	NA	NA	3.5	17
Hay	round bale	6 mil polyethylene	NA	NA	NA	NA	1.65	17
Hay	round bale	polyfabric tarp	NA	NA	NA	NA	1.2	17
Hay	round bale	poly structure roof only	NA	NA	NA	NA	1.2	17
Hay	round bale	poly structure	NA	NA	NA	NA	1.6	17

Appendix E Summary of the literature review, bale storage

Crop	type of bale	storage treatment	period of storage	Initial Moisture content (% wb)	Final Moisture content	dry matter loss (%)	cost ($)	reference
		totally enclosed						
alfalfa	round bale	twine inside	39 weeks	16	17.5	6.7	NA	18
alfalfa	round bale	plastic outside	39 weeks	15.8	20.6	10.2	NA	18
alfalfa	round bale	net - outside	39 weeks	18	24.7	11.6	NA	18
alfalfa	round bale	twine - outside	39 weeks	16.8	23.5	11.6	NA	18

1 - K. J. Shinners et al. (2010) . 2 - K.J. Shinners et al. (1996). 3 - Harrigan and Rotz (1994). 4 - Sanderson et al. (1997). 5 - Huhnke (1993). 6 - Huhnke (1990). 7 - Shinners et al. (2009). 8 - Khanchi et al. (2010). 9 - Harrigan et al. (1994). 10 - Sood et al. (2014). 11- R.L Huhnke (1990). 12 - Collins et al.(1987). 13 - Shinners et al (2006). 14 – Huhnke (1988). 15 - Khanchi et al. (2009). 16 - Huhnke (1990). 17 - Ontario Fact sheet (1988). 18 - Harrigan et al. (1994)