ASSESSMENT OF THE AVAILABILITY OF AGRICULTURAL BIOMASS FOR HEAT AND ENERGY PRODUCTION IN ONTARIO

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ACRONYMS AND ABBREVIATIONS

AAFC: Agriculture and Agri-Food Canada

ac: acre

A_i= seeded area (in hectares) of a crop in a rotation for any given year, where i could be corn (C), soybean (S) or winter wheat (W)

Al: Aluminum

BD: Bulk Density

BIOCAP

bu: bushel

C4 photosynthetic pathway: a biochemical pathway that prevents photorespiration (process that reduces the yield of photosynthesis).

Ca: Calcium

CBIN: Canadian Biomass Innovation Network

CEC: Cation exchange capacity

CHU: Crop Heat Units

Cl: Chlorine

CLI: Canada Land Inventory

CRP**:** Conservation Reserve Program

CS or C-S: Corn-Soybean rotation

CSW or C-S-W: Corn-Soybean-Winter Wheat rotation

Cu: Copper

CV: Coefficient of variation

ERS: Elora Research Station

Fe: Iron

G: Harvested grain

G_{corn}: Harvested grain corn

GHG: Greenhouse gas

GJ/t: Gigajoules per tonne

$G_{soybean}$: Harvested soybean

G_{wheat}: Harvested winter wheat

ha: hectares

HI: Harvest Index

K: Potassium

kg/m^3: kilograms per meter cube

kg/Mg: kilogram per Megagram (i.e. kilogram per tonne)

k_{rec}: Root to Shoot ratio

M: Million

Mg: Magnesium

N: Nitrogen

Na: Sodium

OMAFRA: Ontario Ministry of Agriculture, Food and Rural Affairs

OPG: Ontario Power Generation

P: Phosphorus

PLS: Pure live seed

ppm: parts per million

R: Root biomass (including rhizodeposits)

$RC_{(t)}$: Corn biomass from the current year (root plus stover residue).

RC: Total corn residue [RC]

R_{corn}: Corn root biomass

Res_{min}: Minimum amount of crop residue to retain to ensure sustainability

$RES_{worthwhile}$: The minimum amount of residue required to financially justify harvest

$RS_{(t-2)}$: soybean biomass two years earlier in the rotation cycle (root and above-ground straw residue);

RS: Total soybean residue

$R_{soybean}$: Soybean root biomass

$R_{T(t)}$: average total residue biomass (roots, including rhizodeposits, plus above-ground vegetative parts) of soybean, wheat, and corn

$RW_{(t-1)}$: wheat biomass the previous year (root and above ground straw residue)

RW: Total winter wheat residue

R_{wheat}: Winter wheat root biomass

Si: Silicon

SOC: Soil Organic Carbon

SOM: Soil Organic Matter

SOM_{form}: Rate of SOM Formation [SOM_{form}] from Residue Input

$SOM_{min:}$ Mineralization/decomposition rate of existing soil organic matter.

SRC: Sustainably Removable corn Cobs

SRR: Sustainably Removable crop Residue

SRR_{Cty}: County average removable crop residue

tDM: tonnes of Dry Matter; M tDM: million tonnes of Dry Matter

Tillable land: The land-base available for growing biomass crops productively

$TSRR_{CS}$: Total residue yield under CS rotation

$TSRR_{CSW}$: Total residue yield under CSW rotation

V: Vegetative aboveground biomass

YC_t: Corn residue biomass (roots plus above ground residue) in the current year

YS_{t-1}: Soybean residue biomass (roots plus above ground residue) in the previous year (YS_{t-1})

Zn: Zinc

EXECUTIVE SUMMARY

Modern society is confronted with the task of providing sustainable solutions to the opposing problems of overdependence on fossil fuel-based energy and its attendant impact on global climate change, while maintaining the ability to produce food, feed and fibre for an ever increasing world population. As part of its green policy vision, the government of Ontario has regulated an end to the production of electricity from coal by the end 2014. Although the biomass-based fuel supply is not sufficient to replace all fossil fuel energy, the development of a biomass and bioenergy market has the potential to improve the environmental performances of the electricity and power sectors of Ontario's economy, while providing an added source of income to Ontario farmers. However, there is limited information on the timely supply and sustainable volume of biomass available. This study aims to assess the farm-level economic feasibility and the sustainable availability of biomass from four crop residues (corn stover, soybean and wheat straws, and corn cobs) and two dedicated cultivated, biomass crops (switchgrass and Miscanthus) in common rotation scenarios in Ontario.

Biomass from Crop Residues

A number of major constraints in the procurement of agricultural biomass were identified, including maintenance soil organic matter (SOM), erosion control, biomass combustion quality, and the costs of biomass production and collection, storage and transport. This study focused mainly on SOM maintenance because of its numerous, essential ecosystem services and functions. From a practical agricultural standpoint, SOM is important for two major reasons: 1) as a storehouse of plant nutrients (a 'nutrient bank account'); and 2) as an agent to improve or maintain soil physical properties that prevent or mitigate soil compaction, soil erosion and/or nutrient leaching. Estimates of the amount of crop residue that can be reasonably removed while maintaining current SOM levels is dependent on the rate at which SOM is formed from non-grain biomass produced in common rotation scenarios and the rate at which existing SOM is decomposed. Based on this knowledge, a five-step approach to estimate sustainably removable residue (SRR) in a typical Ontario soil was developed; parameters and variables such as SOM formation and decomposition rates, harvest indices, root-to-shoot ratios, and land areas in rotation, were used in developing the five-step approach.

Above- and below-ground residue volumes are the drivers that determine carbon input levels in SOM formation. Based on the five-step approach, four scenarios were outlined that define how much residue can be sustainably removed: (1) a best case scenario defined by high SOM formation rate and low SOM decomposition rate; (2) a literature average scenario created by conditions with average SOM formation and SOM decomposition values reported in the North American literature; (3) a University of Guelph Elora Research Station (ERS) scenario defined by prevailing conditions in the Western Ontario geographical region and supported with data from a long-term rotation study; and (4) a worst-case scenario defined by low SOM formation rate and high SOM decomposition rate.

The results of our analysis suggest that the possibility of crop residue removal in Ontario is feasible, but practical in only limited locations, which we refer to in the study as ‘qualified lands’. Using the ERS scenario with a loam soil as a baseline, and assuming a typical and common corn-soybean (CS) and corn-soybean-winter wheat (CSW) rotation scenarios, the following counties were identified as having at least 30% eligible land from which crop residues can sustainably be removed:

- all counties/divisions/municipalities in Southern Ontario, except the Niagara Region;
- all counties/divisions/municipalities in Western Ontario, except Halton;
- Durham and Northumberland counties in Central Ontario; and
- Ottawa, Prescott and Russell, and Stormont and Dundas counties in Eastern Ontario.

Under a shorter CS rotation, residue may be removed from fewer counties, namely: Chatham-Kent, Elgin, Lambton, Middlesex and Oxford (Southern Ontario); Huron and Perth (Western Ontario); and Stormont and Dundas (Eastern Ontario). Assuming that the ERS scenario conditions are sufficiently representative of conditions in the majority of the agricultural regions of Ontario, then about 1.1 million tonnes of dry matter (1.1M tDM) residue could be sustainably removed each year. Annual residue removal may, however, actually fall between the values we determined for the best case and the ERS scenarios, depending on soil type, topography, climatic conditions, and management practices. Also, since SRR depends on total biomass yield, an increase in grain yield of the rotational crops would result in increases in SRR due to increases in the number of qualified lands from which residue can be removed and increases in residue amounts that can be removed from existing qualified lands. The impact of grain yield changes as well as the baseline SOC on SRR warrants further study. Our analysis assumed that qualified lands are predominantly flat and that the amount of crop residue needed to maintain SOM is a function of the crop rotation system only. In reality, however, SRR would also be dependent on land slope and tillage practices specific to a particular location. For example, it would be unwise to remove residues from predominantly sandy soils or highly sloped landscapes.

Although corn cobs represent a small percentage of corn residues, they provide an environmentally sustainable alternative feedstock for the bioenergy industry. In this study, we considered corn cobs separately from the other crop residues. Our total annual estimate of sustainably removable corn cobs (SRC) across Ontario was 0.83 M tDM; we assumed that all cobs can be removed and that the rest of the corn stover would be used to meet SOM sustainability requirements. However, this value could still be an overestimation. We currently have very limited knowledge on cobs; very little is known about the actual impact of corn cob removal on essential soil ecosystem services, including SOM_{form}, soil erosion prevention, and nutrient (especially micronutrient) cycling. More research is needed to assess these impacts and to identify the cheapest and safest methods for farm-based corn cob storage.

Management Practices to Enhance Crop Residue Removal

In order to increase soil carbon inputs and enhance the sustainability of residue removal, more sources of carbon inputs need to be included in rotation systems. In general, it appears that the complexity of crop rotation may be the most crucial management practice in regard to sustainable residue removal. Other management practices that would increase soil carbon inputs and help reduce soil erosion include the use of cover crops with prolific rooting systems and vegetative growth in rotations, adding animal manure or compost to field crops, and adding soil amendments that can increase both the active and heavy fractions of SOM. Implementing soil conservation techniques, such as no-till and contour cropping can also help to mitigate the adverse effects of crop residue removal on soil quality and productivity. We currently lack enough data on the impacts of crop residue removal on soil attributes and agro-ecosystem dynamics. Both the short and long-term effects of residue removal on soil properties and environmental quality need to be investigated further on a site-specific basis when making sustainability decisions in regard to residue removal.

Biomass from Dedicated Biomass Crops

Dedicated biomass crops are typically non-food crops grown as feedstocks for the purpose of transportation fuel, energy production and a wide range of industrial end uses. Instead of crop residue, dedicated biomass crops such as Miscanthus and switchgrass among others, could be used for bioenergy production since both species have been reported to produce high yields of biomass with relatively low nutrient addition. Potential biomass productivity in each county of Ontario was determined by assuming percentages of the area of tillable land by quality (i.e. land capability class) that could be allocated to these crops, and also by assuming tillable land-dependent biomass yields. For example, use of only 5% of all tillable lands (i.e. classes 1-5 lands) and can provide over 2M tDM of either switchgrass or Miscanthus biomass assuming all above ground biomass is recoverable. Thus, assuming only 50% biomass recovery due to harvesting inefficiency and/or other technical constraints, and without considering the practicality and economics of biomass procurement, 10% of all tillable land classes can still meet a 2 million tDM yield goal for either switchgrass or Miscanthus.

Breakeven Prices of Agricultural Biomass Procurement

We used break-even analysis to consider the financial feasibility of crop residue biomass as a biomass feedstock. Farmers will not even consider supplying crop residues to the 'aggregator' or power plant unless they are able to at least break even on the sale of the residue. A reasonable break-even price for crop residues considers the harvest costs, the storage costs, and the replacement value of the nutrients lost upon harvest.

The break-even price for crop residues is between \$57/t and \$87/t, and for dedicated crops is \$48.00/t for Miscanthus and \$46.65/t to \$79.97/t for switchgrass, respectively. The breakeven costs cover only production and collection costs and do not cover costs associated with risk, management and other financial considerations, such as the costs of decreased SOM resulting from excess removal. These break-even prices represent an estimated minimum price necessary to cover all variable and fixed costs for the farmer but it does not ensure biomass will be supplied at these prices; the break-even prices are not market prices and do not in anyway indicate economic returns or profit. The actual amount supplied for each biomass price depends critically on the opportunity costs associated with not growing typical crops in the conventional manner.

The results of this study suggest that biomass may be more sustainably supplied (and in greater potential quantity) by dedicated perennial deep rooted biomass crops rather than from crop residue removal. Ontario has an adequate land base for producing Miscanthus and/or switchgrass biomass to meet and surpass the need's suggested by OPG. Furthermore, the Ontario agricultural land base would be able to meet the needs of other competitive uses without significantly affecting the production and supply of conventional or traditional crops. Whether agricultural biomass can be sustainably generated, the actual amount supplied depends on production costs, yields, opportunity costs of production and the price that purchasers are willing to pay.

TABLE OF CONTENTS

SECTION 1: INTRODUCTION

1.1 Background

Modern society is confronted with providing sustainable solutions to the opposing issues of energy and global climate change, while maintaining the ability to produce food, feed and fibre for an ever increasing world population. Ontario is Canada's largest provincial consumer of energy, accounting for more than 30% of the country's total consumption in 2004 (Environment Canada 2003). Ninety percent of provincial primary energy consumption is of fossil-based fuels and the province is the second largest greenhouse gas (GHG) emitter in Canada, behind Alberta (Environment Canada 2003). It was reported that, in 2003, GHG emissions from Ontario's electricity generation were responsible for approximately 20% of the province's total GHG emissions (Environment Canada 2003; Natural Resources Canada 2009). Additionally, this sector of the economy is among the major emitters of air pollutants (Natural Resources Canada 2009). The use of biomass, particularly agricultural biomass, for energy is being considered as part of the solution to the energy and climate change problem. Bioenergy has the potential to improve the environmental performances of the electricity and power sectors of Ontario's economy. In a broader context, agricultural biomass includes animal manure, cellulosic crop residues, fruit and vegetable culls and food-processing effluent, and dedicated biomass crops.

1.2 Ontario's Bioenergy Vision

As part of its green policy vision, the government of Ontario has regulated the phase out of coal in electrical generation by the end of 2014 (Environment Protection Act, 2007). Agricultural biomass can be used to replace a portion of the previously coal based generation since it can generate heat and electricity in existing, large-scale power generation plants (e.g. Ontario Power Generation's (OPG's) Lambton and Nanticoke generating plants), small-scale power generation, cement kilns, greenhouses, and poultry farms, using technologies such as direct combustion of biomass and biomass-integrated gasification combined cycle. In 2003, approximately 28% of Ontario's electricity consumption was generated from coal (Ontario Ministry of Energy 2006), but this percentage has since declined to 7% in 2010.

1.3 Sources of Biomass

The main factors influencing feedstock selection for electrical generation are supply, combustion properties and price (Natural Resources Canada 2009). Biomass in Ontario includes forest residues, virgin cuttings and unused wood, agricultural residues, and municipal solid waste that could provide over 27% of the provincial energy demand (Natural Resources Canada 2009). Recently, there has been increasing interest in the use of agricultural residues (e.g. corn stover, corn cobs, soybean stubble, cereal straw) and dedicated biomass crops (e.g. switchgrass and Miscanthus). Although the biomass-based fuel supply is not sufficient to replace all fossil fuel energy, it can substitute for a percentage of fossil fuels and potentially provide significant reductions in GHG emissions, since the carbon contained in biofuels is biogenic and considered to be renewable. However, there is limited information on the timely supply and sustainable availability of biomass for use on both small and large scales. In particular, the suitability and the economic and environmental feasibility of the use of most agro-based biomass in power generating plants are unknown. More work remains to be done to determine whether crop residues and dedicated biomass crop species are suitable feedstocks for heat and electricity generation in Ontario. OPG estimates its annual biomass supply requirements at about 2 million tDM to convert some units for electrical generation; this biomass volume is the threshold for this study.

1.4 Crop Residue Quality Factors

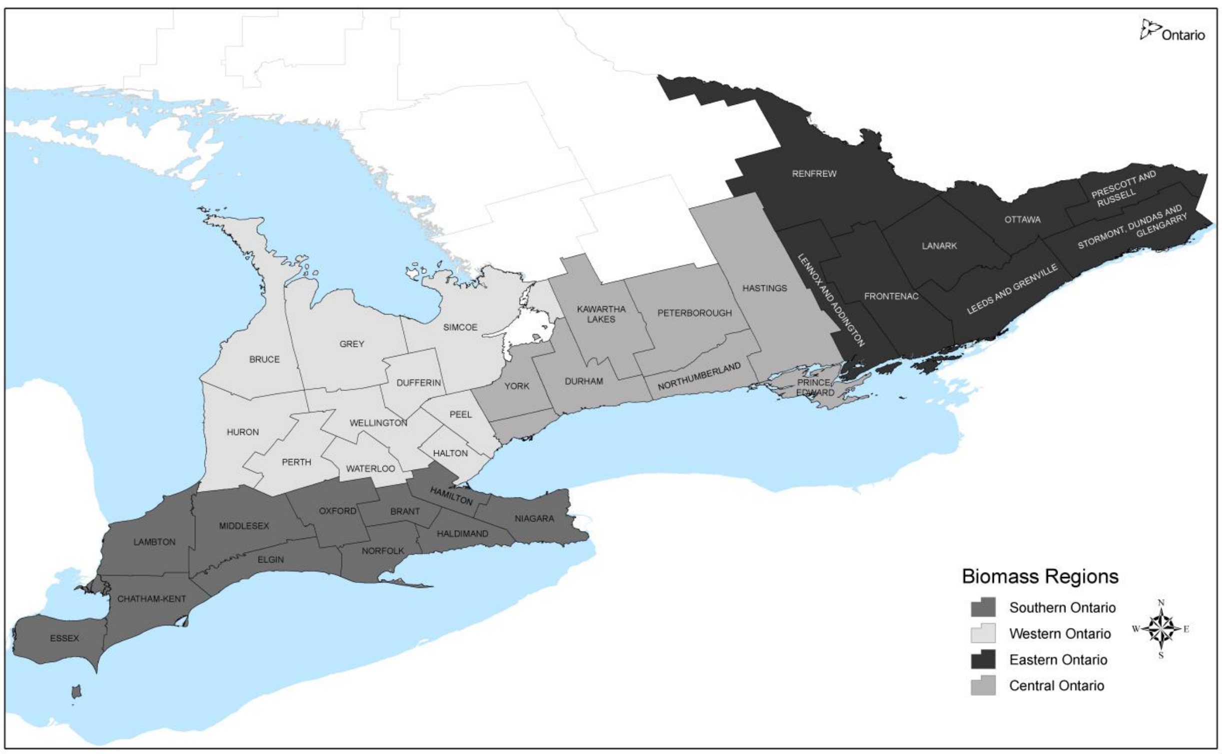
Although popular in Europe, the main barrier to the use of herbaceous biomass for heating has historically been unsuitable biomass quality for combustion systems (Zhang et al. 2007) and the sophistication of the combustion system in use in Ontario. Demonstrations have shown that cofiring could pose technical challenges to coal plant operations because of differences in fuel properties between coal and biomass (e.g. density, chemical composition, energy content, and moisture content) (BIOCAP 2006). For example, potassium (K) and chorine (Cl), when exposed to high temperatures, vaporize from feedstocks, creating corrosive salt formations on boiler walls. These elements agglomerate with silica particles to create clinker formations, resulting in serious performance and operating problems for boilers (Samson et al. 2006). Therefore, the selection of the right types of biomass feedstocks to replace coal in power generating plants and other industries is critical in the development of the bioenergy industry.

It has also been reported that the costs of procuring and handling biomass for use in power generating plants were uncompetitive with those of coal and other fossil fuels (Sami et al. 2001). For example, it has been reported that collection and transportation costs of biomass prior to processing could raise the price of biomass pellets in a power generating plant by 20% compared to coal (Sokhansanj 2006).

1.5 Study Area

The area encompassed by this study is limited to the agricultural counties of Ontario. While there is some agricultural production in Northern Ontario, this area has been excluded due to its comparatively poor growing season and data constraints. The Ontario counties under consideration in this study are shown in Figure 1.1.

Figure 1.1: Map of the selected counties and regions within Ontario for this study



1.6 Study Purpose and Objectives

Although it is relatively easy to estimate theoretically available volumes, estimating realistic biomass availability is more challenging. Actual volumes are constrained by agronomic, environmental, technical, economic, sustainability limitations, and their interactions. A thorough assessment of these limitations is required to better understand Ontario's actual supply capacity of agricultural biomass. Given these limitations, the purpose of this study is to provide realistic estimates of the amounts of agricultural biomass that can be sustainably supplied in Ontario.

The objectives of the study are, therefore, to:

1) Assess the farm-level sustainable supply and economic feasibility of the use of agricultural crop residues in power and electricity generation, in Ontario; and
2) Assess the farm-level potential supply and economic feasibility of the use of cultivated biomass crops in power and electricity generation, in Ontario.

1.7 Overview

After introducing the study in Section 1, the study continues with a discussion of the sustainable availability of crop residues from common Ontario crops, specifically corn, soybean and wheat, grown in rotations (Section 2). Section 3 then isolates corn cobs as a potential source of biomass due to their unique properties that may make them better suited than other residues for combustion. Section 4 examines the potential supply of biomass from dedicated crops, specifically Miscanthus and switchgrass, under specific land classes. The study concludes with a summary and overall discussion of the potential biomass supply in Ontario, in Section 5.

SECTION 2: ESTIMATED SUSTAINABLE BIOMASS AVAILABILITY FROM COMMON CROP ROTATION RESIDUES

Renewed interest in the use of biomass in heat and electricity generation, in Ontario, has been spurred by the provincial government policy to phase out the use of coal by the end of 2014. Crop residues from corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L. Merr.) are considered to be particularly promising sources of biomass due to their concentrated production in Ontario. However, the removal of these crop residues is not straightforward. Crop residues are important in the maintenance and protection of soil quality, which limits the amount that can be removed. Crops are also grown in common rotations in Ontario, which means that availability is most realistically considered on a rotational basis. Other limitations to crop residue procurement and competing uses for these residues also exist.
Part of the lack of information is that Ontario have not had a traditional use of crop residues other then cereal straw, so there was never an interest previously in understanding the implications of residue removal. In the rare cases where residues were harvested, they were mainly used as feed or bedding that was recycled back into the landscape. Consequently, the availability of biomass in the province has not been well established. The purpose of this section is, therefore, to assess the sustainable availability of biomass from crop residues in common Ontario crop rotations, on a county scale.

The specific objectives of the analysis in Section 2 are: 1) to estimate the quantity of crop residue that could be sustainably removed from a farmer's field after grain harvest on a county basis, taking into account county-specific yields, and agronomic, economic and technical constraints; 2) highlight some of the characteristics of crop residues; and 3) estimate the farm-gate cost of collecting common crop residues in a rotation. Essentially, this analysis revolves around four major questions:

1. How much residue is present in a county?
2. How much residue needs to be left in the field to satisfy minimum soil quality sustainability requirements?
3. How much can be reasonably and safely removed after accounting for the minimum soil quality sustainability requirements?
4. How much does it cost to remove crop residue?

The amount of residue required to remain on the field to maintain soil carbon was the major consideration and focus of this section, and the knowledge base for quantitatively assessing that residue amount was based on previous studies (e.g. VandenBygaart et al. 2002; Wilhelm et al. 2004; Lemke et al. 2010).

2.1 Factors Affecting the Sustainability of Crop Residue Removal

Soil sustainability is very important to agriculture and society; crop residues are often left in place, rather than removed, to maintain and protect soil quality, and to provide other essential ecosystem services such as erosion reduction. Consideration of removing crop residues from the landscape must examine the impacts of such a practice on factors such as soil organic matter, nutrient levels and cycling, erosion, and general soil quality indicators (Hargrove 1991; Buyanovsky and Wagner 1997; Clapp et al. 2000; Wilhelm et al. 2004). The impact of management practices such as crop rotations on soil carbon dynamics also need to be considered.

Soil Organic Matter

Crop residue together with plant roots and their exudates are the primary source of C in our agricultural ecosystems. Several studies indicate the importance of crop residues in building soil organic matter (SOM) levels, a key factor positively related to soil quality and crop productivity (Larson 1979; Lindstrom 1986; Lindstrom et al. 1979; Nelson 2002). The term SOM encompasses all organic components of a soil. These components include: 1) raw plant residue and microbial biomass; 2) ‘active fraction/light fraction’ made up of microbially modified compounds and by-products of decomposition, mainly polysaccharides from plant sources, and polyuronides (synthesized by soil microbes), with relatively rapid turnover rate; and 3) ‘humus/heavy fraction’, the relatively stable form of SOM associated with clay and silt which provides stability and resistance to decomposition. Raw plant residues on the soil surface reduce erosion by water and wind, while the ‘active fraction’ enhances soil aggregation for good soil structure, water infiltration, resistance to erosion and crusting. The humus fraction, comprising 60-80% SOM, functions in a nutrient holding capacity/cation exchange capacity (CEC) by adsorbing and holding nutrients in plant-available form, and it also increases the water-holding capacity of the soil.

Soil organic matter contains an average of 58% carbon, referred to as “soil organic carbon” (SOC), as well as nutrients such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and many micronutrients. With the high percentage of SOC in SOM, the terms SOC and SOM are often used interchangeably. However, the SOC content in soils may range from less than 1%, in sandy soils, to almost 100%, in wetland soils (Brady and Weil 1999). Soil organic matter serves several ecosystem services and functions, but from a practical agricultural standpoint, it is important for two major reasons: 1) as a storehouse of plant nutrients (a “nutrient bank account") and; 2) as an agent to improve or maintain soil physical properties, such as structure and tilth, and minimize erosion (Albrecht 1938; Franzluebbers 2002). It also buffers soil from significant changes in acidity/alkalinity (soil pH). The amount of SOM/SOC in a soil depends on soil texture, climate, input of carbon from primary production, and historical and current land use/management. Soil texture affects SOC because of the stabilizing properties that clay and silt have on organic matter (Voroney et al. 1981). In addition, clay offers chemical protection to organic matter through adsorption onto clay surfaces, which reduces the rate of SOM decomposition by microbes (Campbell et al. 1996). Soils with high clay content, therefore, tend to have higher SOC than soils with low clay content, under similar land use and climate conditions. Climate affects SOC as it is a major determinant of the rate of decomposition (mineralization) and, therefore, the turnover time of carbon (C) in soils.

Soil organic matter influences soil structure through soil aggregation and aggregate stability (Tisdall and Oades 1982; Six et al. 1999). The aggregates and their stability, in turn, have tremendous influence on infiltration of water, soil water-holding capacity, and soil bulk density and aeration (Carter 2002). Loss of SOM has been identified as a major cause of soil degradation in Ontario (Miller 1986; Miller 2009; Dumanski et al. 1986). Currently, there is limited research on the long-term effects of residue removal on Canadian soils (Ellert and Gregorich 1996) and addressing this potentially serious shortcoming becomes even more important as the use of agricultural biomass for the bioenergy industry is being promoted. Follett (2001) indicated that if all other factors are constant, SOM content is dictated by the quantity of residue returned to the soil. Several other studies also reported the positive relationship between SOM and the amount of residue returned to the soil (Maskina et al. 1993; Gilley et al. 1986; Gregorich et al. 1998). Similarly, Robinson et al (1996) reported a positive linear relationship between the amounts of corn residue added in moldboard-plowed fields and the level of SOC in the surface 15 cm. This is consistent with the report of Ellert and Gregorich (1996) who studied the storage of carbon, nitrogen and phosphorus in cultivated soils in Ontario, and noted decreases in C storage due to reduced C inputs and enhanced rates of plant litter decay. In a study covering a 13-year period in Minnesota, USA, Clapp et al. (2000) reported the roles of residue, tillage and N fertilization in soil organic matter accrual by determining the source of C in the organic matter. All three management factors affected SOC storage. According to Wilhelm et al (2004), tillage and residue management variations create a complex association of soil and surface conditions that both directly and indirectly influence the performance of crops such as corn. For example, studies showed improvement in crop yields through retention of essential nutrients, protection from raindrop crusting (Blevins et al 1983) and conservation of soil water (Doran et al. 1984). However, in some studies, crop residue coverage has been observed to decrease yields because of poor weed control, excessively wet and cold soils, and poor seed placement (Swan et al. 1994). It is, therefore, imperative to have some level of knowledge about the impact of residue removal on soil quality attributes and crop yield before attempts are made to remove residue on a commercial scale.

Nutrients

Residue removal reduces nutrient pools by: 1) removing the nutrients contained in the residues; 2) increasing risks of runoff and soil erosion, which further remove nutrients; and 3) accelerating SOM mineralization at the bare soil surface because of alterations in soil temperature and moisture regimes. According to Wilhelm et al. (2004), including residue harvest removes more nutrients from the agro-ecosystem than grain harvest alone. Although corn residue does contain significant amounts of macronutrients, the major contribution of agricultural residue to the soil is SOC (Allmaras et al. 2000). Lindstrom (1986) reported net losses of nutrients for high residue removal rates in no-till corn, suggesting that increased fertilization rates are required to maintain soil fertility. Conversely, Power and Doran (1988) found that increasing residue return rates increased total N uptake (i.e., immobilization) from soil, suggesting that added N fertilizer was required when residues remain, to avoid soil mining for residue decomposition. Clapp et al. (2000) reported similar results in no-till corn, noting that added N fertilizer increased residue-derived carbon sequestration. In comparing various removal rates in no-till and conventional tillage with incorporated residues, Karlen et al. (1984), found that harvesting crop residues increased macronutrient removal, decreased soil cover, but had a varied effect on corn grain yield.

Erosion

The reduction of erosion is probably the most often cited reason for retaining at least some agricultural residue. Soil surface residues protect soil from wind and water erosion, and increase soil resistance to runoff events. Effects of erosion include decreased plant-available soil water holding capacity, root restriction and increased soil bulk density (Mann et al. 2002). Numerous studies of residue removal effects on erosion use simulation models (Lindstrom et al. 1979; Graham et al. 2007). For example, using the Universal Soil Loss Equation (USLE) model, Lindstrom et al. (1979) predicted that, in general, residue removal rate had a greater effect on soil loss than tillage, with soil loss highest in conventional tillage fields with high residue removal and lowest under no-till conditions with low residue removal. However, in a review of numerous field studies, Benoit and Lindstrom (1987) reported that no-till without residue often results in more soil erosion than conventional tillage, but no-till with residue cover usually results in less soil erosion than conventional tillage, highlighting the importance of the tillage-residue interaction when assessing the effects of residues on soils.

Tillage and Crop Rotation

Agricultural practices affect the level of SOC by influencing the amount of residue returned to, and retained by, the soil (Liang et al. 1998). Two separate Canadian studies by Angers et al. (1995) and Lemke et al. (2010) showed that the incorporation of corn-derived C into SOM was not affected by tillage (agricultural preparation of the soil by ploughing, ripping, or turning it). Angers et al. (1995) and, later, Deen and Kataki (2003), also found differences in the vertical distribution of SOM, but not the rate of SOM turnover among tillage depths. Similarly, Clapp et al. (2000) reported that stover harvest over 13 years under Minnesota conditions, did not affect SOC in the surface 0 to 15 cm, compared with the residue-returned treatment, if the plots were tilled annually (moldboard or chisel-plowed) and had low N input. The latter study also indicated that the combination of returning stover and adding N fertilizer slowed decomposition of relic SOM, while the combination of removing stover and adding N increased the decomposition of relic SOM.

The amount of crop residue that can be harvested would also be influenced by crop rotation depending on the quantity of root and above-ground residue produced in the rotation. In a study on the impact of crop rotation and tillage on carbon sequestration in Canadian prairie soils, McConkey et al. (2003) reported that annually cropped rotations sequestered substantially more carbon than rotations including years of bare fallow. In an earlier study, West and Post (2002) concluded that enhancing rotation complexity would result in significant accumulation of SOC. Including forages in the crop rotation is one of the simplest ways to improve soil quality. Several researchers reported the agronomic and environmental benefits of rotating forage crops with annual grain crops to include higher grain crop yields following forages, improved soil quality, weed control, increased carbon sequestration, retrieval of deeply leached nutrients, and critical habitat for wildlife (Russelle et al; 2006; Martin et al, 2001; and Hodgson, 1976).

Impact of Crop Residue Removal on Grain Yields

Several studies have examined the effect of stover harvest on subsequent yields, both in the short and the medium term. For example, Blanco-Canqui et al. (2006b) found that the site-specific effects of stover management on corn yield could be observed a single season after implementation of differential residue retention rates. Karlen et al. (1984) found no differences between treatments when yields were averaged over three-years and concluded that some residue could safely be harvested for biofuel production, provided that residue nutrients were replaced by additional fertilization. Power et al. (1986) found increased crop yields for corn and soybean when residues were left on the soil surface compared to residue removal in Nebraska. In another Nebraska study, in which Wilhelm et al (1986) applied four residue-return treatments (0, 50, 100, and 150% of that produced) over five years, the results showed a negative linear response between grain yield and residue removal. Grain and biomass yields were reduced by 0.13 t/ha and 0.29 t/ha, respectively, for each t/ha of corn residue removed in the previous season. In a follow up three-year study, Maskina et al. (1993) showed that a significant yield differential between the 150 and 0% residue return treatment continues, despite the fact that the earlier treatments had been discontinued. Their results demonstrate that treatments with increased rates of residue (100, 150%) returned had increased the organic carbon and total nitrogen in the upper level of the soil from their initial levels. This yield effect was most pronounced in drier years, leading them to attribute yield increases to residue-induced water conservation. In a similar report, Linden et al. (2000) found that corn yields in treatments involving corn residue retention exceeded those with no residue by approximately 22% in drier than average years. Other studies have suggested that removing residue would increase yields by allowing quicker emergence and decreasing over-wintering sites for pests and diseases (Kaspar et al. 1990; Swan et al. 1994). Yet, other studies on residue removal impacts have reported reduced yields due to lower soil temperatures that result in poor germination and/or delayed emergence and silking (Swan et al. 1987; Dam et al. 2005), although, as demonstrated by Blanco-Canqui et al (2006b), accelerated emergence and early growth in low residue plots does not necessarily translate to yield gains. However, Dam et al. (2005) found no differences in grain yields or dry matter yields over an 11 year study period on sandy loam soils where residue return rates were compared.

General Soil Quality Indicators

With respect to soil quality, Karlen et al. (1994) reported that 10 years of residue removal under no-till and continuous corn resulted in deleterious changes in many biological indicators of soil quality, such as lower soil carbon, microbial activity, fungal biomass, and earthworm populations, compared with normal or double rates of residue return. Reduction in these properties and populations suggests loss of soil function, particularly reduced nutrient cycling, physical stability, and biodiversity (Karlen et al. 1994). Stover return has also been shown to make positive changes in physical indicators of soil quality, such as soil texture, soil and root depths, infiltration, soil bulk density, and water holding capacity (Liebig et al. 2004; Clapp et al. 2000; Doran and Parkin 1994). Although Dam et al. (2005) found no changes in soil bulk density associated with corn residues under some Canadian conditions, Clapp et al. (2000) found reduced bulk density in tillage treatments that included crop residues.

The literature reviewed on the sustainability of crop residue removal suggests that quantities of crop residue that can be sustainably harvested are directly influenced by several factors, including existing SOM levels, carbon input from primary production (below-ground roots and above-ground crop residues), climate, soil characteristics, and crop management practices (Wilhelm et al. 2006). These factors and their interactions explain why decreased crop residue retention could lead to reduced in grain yields.

2.2 A general description and the production requirements of specific residue types

This study focuses on the most likely field crop residues that may be used as biomass feedstock for the bioenergy industry in Ontario. Corn stover, soybean straw and wheat straw were selected as the best candidates due to their prevalence in Ontario. However, their characteristics are not necessarily advantageous for use in heat or electricity generation and the crops are certainly different. Table 2.1 gives a brief overview of some of the more relevant production and use characteristics of the biomass residues.

Table 2.1: Relevant production and use characteristics of corn stover, corn cobs, soybean straw, wheat straw, and bituminous coal, including ash content, moisture content at harvest, bulk density, carbon content and heating value.

Characteristics	Ash Content (% Dry Weight)	Moisture Content at Harvest (%)	Bulk Density (Pre-Processed) (kg/m^3)	Carbon Content (% of Dry Mass)	Heating Value (GJ/t)
Corn Stover	5.7[a] 13.1[b]	30.0-50.0[e] 34-50[b]	144[l]	42.69±1.47[b]	18.40[e] 16.6[b]
Corn Cobs	7.5[b]	28-38.5[f]	272[l]	44.53±0.5[b]	18.4[h] 17.0[b] 18-19[g]
Soybean Straw	6.5-10.0[c] 7.9[d]	8.6-7.1[b]	NA	42.11±2.12[b]	19.10[h] 17.0[b]
Wheat Straw	7.5[b]	9.3[b]	79[e]	43.16±1.13[b]	18.4[e] 18.9[n] 16.5[b]
Bituminous Coal	9.0[j] 20±3.4[b]	11.0[j] 2.8b	NA	NA	28.2[n] 34.0[b]

[a]Hoskinson et al. 2007
[b]Cuiping et al. 2004
[c]Samson et al. 2000
[d]Bakisgan et al. 2009
[e]Reisinger et al. 2006
[f]Smith et al. 1985
[g]Clark and Lathrop 1954
[h]AURI 2001
[i]Preston 2005
[j]McKendry 2002
[k]Wilcke and Wyatt 2002
[l]Watson 2003
[m]Braisher et al. 2006
[n]Nordin 1994

Ash content, moisture level and heating value all affect the use of biomass residues for heat and energy production. Higher ash and moisture contents are detrimental to combustion and are, therefore, undesirable. The ash content of crop residues is typically lower than for bituminous coal (Table 2.1). Unlike coal ash, which may contain high levels of toxic metals and other contaminants, the ash from crop residues may be used as a soil amendment to replenish nutrients removed by harvest. A higher heating value is preferable, as it indicates the amount of energy provided upon combustion. A general description and the production requirements of the specific residue types are discussed below.

Corn Stover

By definition, corn stover is the total above-ground corn plant composed of several identifiable components including stalks, husks, shanks, silks, leaf blades, leaf sheaths, tassels and cobs, which are normally left in the field after grain harvesting . Overall, husks, shanks, silks and cobs account for 30% of the stover mass, while stalks, tassels, leaf blades and leaf sheaths account for the remaining 70% (Hoskinson et al. 2007).

Among field crops in Ontario, corn has the greatest potential for biomass volume because of the large amount of residue produced and its highly concentrated growth area, particularly in the Southern and Western geographical regions of the province. Ontario is the single largest Canadian corn production region and accounts for 5.8 million tonnes of grain in 2005 (Burroughs and Smith 2005). Estimates of annual corn grain production in the province have seen progressive increases in tonnage since 2004. The average production between 2004 and 2008 is estimated to be 6.2 million tonnes per annum. Assuming a 1:1 ratio, an equal amount of grain and corn stover is produced. Except for the colder northern counties, corn is grown in all other counties in Ontario, excluding Halliburton, Muskoka, and Parry Sound counties in the Central geographic Region, and thrives under varied soil types, including silt loams and heavy clays, at soil pH levels between 6 and 6.5. Corn is grown widely across the Southern, Western and Eastern regions of the province, mainly on class 1-4 soils. Silty-loam soils are considered the most productive because of lower nitrogen requirements. In areas where heavy clays are predominant, additional N fertilizer requirements are needed. Similarly, additional amounts of nitrogen may be required for optimum yields. However, recommended fertilizer application rates are site-specific.

Corn-soybean (C-S) and corn-soybean-wheat (C-S-W) rotations are the two major rotation systems practiced across Ontario. Corn-corn monocropping is also practiced in some areas, albeit on a small scale. Rotational systems provide several benefits, including lower disease and pest build-up, reduced nitrogen use and better weed control. Tillage systems for cultivating corn in Ontario include: 1) conventional tillage, consisting of fall mouldboard plowing, chisel plowing or heavy disking, followed in spring by secondary tillage, usually with a field cultivator or tandem disk; 2) fall mulch tillage which leaves a significant amount of crop residue on the soil surface and is conducted with a wide range of equipment types including, chisel plows, cultivators, vertical tillage implements, etc; and 3) no-till systems that use field operations involving little or no disturbance to the field surface. While much of the cereal and soybean crops are planted using no-till systems, the majority of the corn crop is planted following some form of medium to aggressive tillage practice.

In this study, a harvesting index of 0.5 (i.e. 1:1 grain to stover ratio) was adopted, as reported in the literature (Perlock and Turhollow 2003; Banzigar et al. 1999; Edmeades et al. 1999). Corn residue has sometimes been harvested for use as animal feed, bedding and/or cattle grazing in counties with more intensive beef cattle production. In Ontario, corn stover harvest time is limited to a short three-month period in the fall (October – December) after the grain has been harvested. In locations where stover is baled for livestock use, farmers normally use existing farm equipment. It is likely that if stover harvest becomes more widespread the short harvest window would pose a serious challenge to harvesting stover in bales. Alternative harvest methods would, therefore, have to be developed to overcome this problem.

During grain harvest, the residue remains in the field. The design of the “corn header” breaks off the cob from the vegetative part of the plant so that only the husk covered cob enters the threshing unit of the combine. The remained of the plant remains in the field, often still attached to the ground by the root system.

Collection of residues from the field often uses hay and forage handling equipment and entails some combination of mowing, chopping, raking and baling. Harvesting stover following grain harvest may be challenging since the residue is left on the ground and a significant amount can be trampled by field equipment (combine, trucks, grain buggies and wagons), leading to a substantial amount of biomass not available for collection. Increased soil compaction due to the additional field traffic can also be a problem (Pordesimo et al. 2002; Perlack and Turhollow 2003). In addition, retrieving corn residue from the ground can result in dirt, stones and trash contamination, reducing the combustion quality of the material.

Single-pass systems are being developed where collection equipment is hitched directly behind the combine to catch the residue stream (stover and/or cobs). The advantages of the single-pass system over separate baling operations include reduced cost, reduced soil compaction, simplified logistics, less contamination of the residue with soil, less susceptibility to late season weather damage and reduced biomass losses (Atchison and Hettenhaus 2004). One of the dilemmas with one pass harvesting of grain and stover is the impact on the harvesting equipment and efficiency. Corn yields are significantly higher then cereals and soybeans so the combine is working harder. Farmers are concerned with reduction in harvest speed and added wear on their equipment by putting all the extra biomass through the combine. Research is looking at ways to equip combines to collect corn residues with the combine without sending all that material through the thrashing unit of the combine.

A significant problem associated with one-pass systems is that the moisture content of the stalks can be very high, typically in the range of 50% or more in Eastern Canada, and may require further drying at extra cost (Savoie and Decouteaux 2004). The latter researchers concluded that single pass systems may be possible in the drier areas of the US Midwest, but they do not seem practical for Eastern Canada.

Collection of corn cobs direct from the grain combine has been done in parts of the US Midwest for many years. This involves a relatively simple modification of the combine and since cob volumes are low relative to total corn stover, do not significantly reduce grain harvest efficiency. However, the management of high moisture corn cobs can pose significant issues as identified above for whole crop stover.

Corn stover collection can deplete soil carbon and nutrients, increase erosion, and reduce crop productivity. With such agronomic, environmental and sustainability constraints, as well as technical factors, involved in harvesting corn stover, only a fraction of the amount produced may actually be recoverable for use as a biomass feedstock.

Two major problems linked to stover use for heat and electricity generation include the relatively high moisture content at harvest (Table 2.1), which makes storage quite challenging, and the removal of the bulky biomass on wet soils during the fall. In addition, as shown in Table 2.2, which details some additional characteristics of corn stover, this residue has high levels of potassium (K) and chlorine (Cl) that make the combustion process difficult. To overcome these problems, spring harvesting of stover is a possibility, since the residue is drier and the over wintering periods helps to leach out the K and Cl. Additional nutrient information, which has implications for sustainability, if nutrient levels are depleted, is presented in Table 2.3. In general, the concentrations of the chemical elements in crop residues vary with respect to biomass type (Tables 2.2 and 2.3).

Table 2.2: Ash-forming element characteristics of corn stover, corn cobs, and wheat and soybean straw.

Characteristic	Element	Corn Stover	Corn Cobs	Wheat Straw	Soybean Straw
Ash-forming Elements	**Al (ppm)**	4111.2±4307[a]	2214± 2229[a]	2052±2459[a]	1336±1012[a]
	Ca (ppm)	9226±4213[a]	9807± 6793[a]	6527±3877 [a]	16159±1181[a]
	Si (ppm)	61±71[a] 268[b]	21±14[a]	170±97[a]	15±12[a]
	K (ppm)	14,302±7683[a] 96,110[b]	14,380±4441[a]	15,659±3718[a]	9,986±2773[a]
	Na (ppm)	571±674[a] 956[b]	269±82[a]	319±271[a]	161±73[a]
	Mg (ppm)	4767±2345[a] 2000[b]	2310±1316[a]	2491±1308[a]	7613±996[a]
	P (ppm)	1849±942[a] 11,177[b]	1299±584[a]	1123±1047[a]	1560±579[a]
	Cl (%)	0.27[c]	0.16[c]	0.15±0.10[d]	NA

[a]Cuiping et al. 2004 ;
[b]Garivait et al. 2006
[c]Hoskinson et al. 2007
[d]Nordin 1994

Table 2.3: Micro and macro-nutrient characteristics of corn stover, corn cobs, and wheat and soybean straw.

Characteristic	Element	Corn Stover	Corn Cobs	Wheat Straw	Soybean Straw
Macro-nutrient Concentrations	N (mg/g)	10.6[e] 10.9[f] 10.0[g]	3.3[h] 4.8[i] 5.1[e]	4.4[i] 7.0[j] 7.6-9.6[f]	8.0[i] 23.0[j]
	P (mg/g)	0.79[c] 2.3[e] 2.0[j] 0.99[g]	1.1[h] 0.9[e]	1.0[j] 0.45-1.05[f]	2.0[j]
	K (mg/g)	6.20[h] 6.74[c] 5.06[g]	8.0[i] 10.5[e]	13.0[i] 10.0[i]	6.0[i] 10.0[j]
	Ca (µg/g)	5.40[c] 5.70[e] 5.13[g]	1.2[ie]	1.6[i]	15.9[i]
	Mg (µg/g)	4.00[c] 2.30[e] 5.13[g]	0.7[e]	NA	NA
Micro-nutrient Concentrations	Cu (µg/g)	1.2[c] 0.7[g]	NA	NA	NA
	Fe (µg/g)	51.0[c] 196.0[g]	NA	NA	NA
	Mn (µg/g)	13.0[c] 43.0[g]	NA	NA	NA
	Zn (µg/g)	9.0[c]	NA	NA	NA

[a]Cuiping et al. 2004
[b]Garivait et al. 2006
[c]Hoskinson et al. 2007
[d]Nordin 1994
[e]NRC 2010
[f]Shomberg and Steiner 1999
[g]Blanco-Canqui and Lal 2009a
[h]Hanway 2007
[i]Preston 2005

Other practical considerations in harvesting corn stover, such as logistics, nutrient replacement, harvest technology, potentially negative soil impacts and many other questions need to be addressed. Recently, Agriculture and Agri-Food Canada (AAFC), in collaboration with the Canadian Biomass Innovation Network (CBIN), initiated a research project to improve harvest systems that reduce biomass losses, improve/preserve biomass quality and cleanliness and reduce the cost of biomass collected.

Soybean Straw

Soybean production in Ontario has seen progressive increases in tonnage since the 1980s (OMAFRA, 2010). This increase has been attributed to many factors, including the development of earlier maturing varieties, improved yield stability, adaptability to various tillage systems, relatively low costs of production, and an expansion in soybean demand. Soybean has been shown to be very responsive to crop rotation systems (OMAFRA 2002) and is cultivated mainly in rotation with corn and winter wheat (e.g. corn-soybean; corn-soybean-winter wheat; winter wheat-soybean). Therefore, soybean is grown in areas within Ontario where corn and wheat are also grown in rotation. In several field trials, a corn-soybean-winter wheat rotation provided the greatest yield response, while continuous soybean had the lowest yield (OMAFRA 2002). Soybean yield losses have been attributed to pests such as weeds (e.g., cocklebur, giant ragweed and pigweed), insects (e.g., seedcorn maggots, slugs, soybean aphids, and defoliating insects) and diseases (e.g., seedling blights, root rot, mildew, and nematode and virus diseases). Research indicates that a short rotation leads to a build up of some of these pests and diseases, and other long-term problems (OMAFRA, 2002). However, most of these pests can be controlled by pesticides and/or the choice of appropriate varieties. Soybean grain yield is also affected by several factors, including seed quality, seed inoculation, planting date, seeding rates, planting depth, and rates and methods of phosphate (P) and potash (K) fertilizer application.

Soybean harvesting normally occurs between September and October. At harvest, soybeans are direct-combined (where the entire plant minus the leaves pass through the combine) at moisture levels below 20%. Compared to corn, soybean does not produce large volumes of residues and post-harvest soybean residues are not adequate to maintain soil cover through the winter. Soybean straw is difficult to recover as natural degradation processes result in leaf senescence by the time the seed pods are sufficiently dry for harvest. In addition, the straw decomposes very easily (Barraco et al. 2007; Kaboneka et al. 1997) and is not generally considered harvestable except where conservation tillage systems are used (OMAFRA 2002). Such conservation practices (e.g., no-tillage) vary from region to region within the province. Hence, the yield of sustainably removable soybean straw could be low even when soil conservation practices are adopted (OMAFRA 2002). The OMAFRA report suggested that winter wheat be no-till planted into soybean fields to help protect fields from erosion. Thus, most of the acreage of winter wheat in Ontario is currently planted soon after soybean harvest using no-till methods. In estimating soybean straw values, a harvest index of 0.5 was used (Table 2.1), as reported in the literature under various conditions (Ferris et al. 1999; Morrison et al. 1999).

Wheat Straw

Wheat is the largest acreage cereal crop and one of the most productive field crops grown in rotation with other crops in Ontario (8% of Canadian wheat). Thus, wheat provides substantial economic benefit to Ontario (OMAFRA 2002). Although spring wheat is grown in Ontario, it is winter wheat, grown in rotation with other crops, especially soybean and corn, which is being considered in this study. The crop is grown in sandy loam to heavy clay soil textures. Specific fertilizer requirements for winter wheat are based on soil types. Since winter wheat requires vernalization (a period of cold temperature between $0^{o}C$ to $5^{o}C$ that induces the crop to elongate, head, flower and produce grains), it can be planted at any time during the fall season until freeze-up. A grain yield of about 3.8 t/ha is obtainable in Ontario (Statistics Canada 2007). Although, in a recent research report, Graham et al (2007) reported a harvest index (HI) of 0.57 for wheat, in this review, a slightly more conservative HI of 0.5 was assumed, as reported elsewhere in the literature (e.g., White and Wilson 2006).

The quality of winter wheat grain declines rapidly following maturity and, thus, requires timely harvest to ensure the highest quality. Soybeans and corn are less susceptible to these quality losses, but are susceptible too depending on weather conditions and the state of the crop going into harvest. At harvest, grain moisture content ranges between 16% and 18%, while straw moisture content varies between 8.3% and 25% (Cuiping et al. 2004). In a recent study on the effects of moisture content on pellet density and stability, results showed that low moisture content (13%) produced higher density and stability than high moisture contents (20% and 25%) (Xiaoxu et al., 2010).

2.3 Constraints and Limitations in Crop Residue Procurement

Moisture content of crop residues at harvest poses one of the major technical problems in residue procurement (Cuipping et al. 2004). In general, thermal conversion requires low moisture content feedstock (<50%) (McKendry, 2002). For example, in a study conducted in Eastern Canada, Savoie and Decouteaux (2004) noted that a main problem with fall harvest is the high moisture content of crop stalks (especially for corn stalks), which are typically in the moisture range of 50% or more. In Ontario, corn is harvested in the late fall when soils are generally in a humid state. For post-harvest crop residues, moisture levels in harvested biomass materials are influenced by time of harvesting, the local climate and treatment after harvesting. In addition, hauling large amounts of biomass off fields in wet fall conditions could lead to serious soil compaction problems. Potential contamination of the harvested biomass by soil and other materials, which can deleteriously impact biomass combustion quality, may also be high. Ash and alkali metal contents are examples of crop residue parameters that could be affected by such contaminants. Savoie and Decouteaux (2004) noted that drying the material to 12% moisture would add extra procurements costs and that dry storage was only practical for material that could be field recovered at 30% moisture or less. However, soybean straw/stalk is relatively dry at the time of harvest with an average of only 22% moisture content.

Normally expressed in kg/m^3, an important characteristic of biomass materials is bulk density (BD), which greatly impacts transport and storage costs. The density of the processed product could influence fuel storage requirements, the sizing of the material handling system and how the material is likely to behave during subsequent thermo-chemical/biological processing as a fuel or feedstock (Perlack and Turhollow 2002). For example, the relatively low BD for wheat straw predisposes this biomass type to the highest transport and storage costs (Perlack and Turhollow 2002).

2.4 Competing Uses of Crop Residue

Table 2.4 provides a summary of competing uses of crop residues.

Table 2.4: A summary of competing uses of crop residues.

Current and Potential Future Competing Uses	Biomass Type: *Corn Stover*	*Corn Cobs*	*Wheat Straw*	*Soybean Straw*
Feed for Livestock (e.g. Dairy Cattle)	X[1]	X	X	X
Bedding for Livestock	X	NA	X	NA
Insulating/Building Materials	X	NA	X	NA
Medium for Mushroom Propagation	NA[2]	X	NA	NA
Particle Board	X	NA	X	NA
Direct Combustion/Gasification	X	X	X	X
Pellets/Briquettes for Large-scale Energy production	X	X	X	X
Paper	X	NA	X	NA
Industrial Uses/Biomaterials/Biochemicals (e.g. furfural)	X	X	X	X
Transportation Fuel (e.g. Cellulosic ethanol)	X	X	X	X

[1]X= Competing biomass use; [2]NA =information not available.

In Ontario, small acreages of corn stover (5%) are currently used for several purposes, including feed and bedding for livestock, insulting material in the building industry, particle board, paper, and chemicals such as furfural. New uses of corn stover currently under development include fibre in biocomposites for the automotive and building industries and bioethanol production. It is projected that lignocellulosic ethanol production will become a viable industry and could create a large annual market for corn stover in the USA (DiPardo 2000) and worldwide (Kim and Dale 2004). Overall, soybean straw has very limited competing uses in Ontario. The literature does report its use in the production of chemicals, such as furfurals, and traditional uses such as livestock bedding and forage, but such uses are still very limited. The main advantage of soybean straw lies in its relatively low K content.

Wheat straw is known to have many traditional uses, including livestock bedding, insulation, straw board and other bioproducts. The amount that a producer is prepared to remove and supply to an industrial user depends on the producer's perceived value of straw (Watson et al. 1998). Although considered a valuable renewable biomass resource, there are serious barriers to the economic use of wheat straw, in general. Some of the undesirable characteristics that make straw less suitable as a bioenergy feedstock are related to its quality, cost of collection, transport and storage (Sokhansanj et al. 2006). For example, wheat straw ash percentage and ash-forming elements, as well as N content, are higher than those of corn cobs (Tables 2.1 and 2.2). For cost-effective utilization of the straw, the undesirable components must be removed and the desirable components selectively harvested. Thus, the commercial use of wheat straw in the bioenergy sector could be limited, in part, by high pre-treatment costs.

2.5 County Level Estimates of Average Crop Residue Availability in Ontario

The single most important challenge concerning residue harvest in Ontario on a commercial scale, beyond traditional uses and quantities, is sustainability, although the perception among both agriculturalists and industry is that it is logistics. Sustainability issues, such as soil organic matter (SOM) levels, soil erosion control, general soil health, depletion and costs of nutrients, and long-term soil productivity, have to be addressed before considering residue removal from Ontario lands. Ontario soils are characterized by reduced carbon inputs and high SOM decomposition rates, which would impact the amount of residue available for removal (Ellert and Gregorich 1996; Bolinder et al. 2007). In a recent paper, Blanco-Canqui (2010) cautioned on the long-term implications of crop residue removal on soil quality and productivity. Our analysis focused primarily on the amount of post-harvest residue that needs to remain on the field to maintain soil organic matter levels, reduce water and wind erosion, and ensure long-term soil health and productivity, under various cropping systems. Most approaches in the literature estimate crop residue amounts needed to control erosion (e.g. Graham et al. 2007; Nelson 2002; Nelson 2003); however, such an approach has been shown to grossly underestimate SOM requirements (Wilhelm et al. 2007).

Johnson et al. (2006) and Wilhelm et al. (2007) used several literature reports on changes in SOC with various levels of crop residue removed to estimate quantities of source carbon needed to maintain SOC. For example, Johnson et al. (2006) reported that 3.0 $\pm$ 1.0 Mg C/ha/yr was required to maintain SOC, under corn production and mouldboard plough tillage. Under no-tillage, 2.1 $\pm$0.1 Mg C/ha/yr was required. These estimates were then converted to stover input. Although the above approach relies on well-documented values of ‘minimum annual source carbon inputs (MSC)’, from several studies in the literature, it is limited in use because the MSC values referenced may not be applicable to Ontario conditions and, most importantly, no MSC values are available for rotation complexities that involve more than two crops (e.g. corn-soybean-wheat systems).

To ensure the sustainable harvest of crop residues under rotation systems, a five-step approach was developed. The greatest emphasis was placed explicitly on SOM resulting from residue retention, considering SOM's role in soil quality, nutrient cycling and production capacity. The five steps include:

1. Estimating the minimum amount of residue required to be left in the field to maintain current soil organic matter levels;
2. Estimating above-ground residue remaining following grain harvest under a rotation system (i.e. above-ground post-harvest residue less the grains);
3. Estimating below-ground root residue (including rhizodeposits), produced under a rotation system;
4. Estimating total crop residue (below-ground and above-ground residue) in a rotation system;
5. Estimating realistic, county level crop residue availability in a rotation and the percentage land area from which residue may be removed.

The Chatham-Kent Division was used to illustrate our procedure for estimating removable residue in typical cropping systems in Ontario.

Step 1: Estimating the minimum maintenance soil organic carbon (SOM_{min}) and corresponding minimum total residue to retain (Res_{min})

In order to quantify the amount of residue that can be sustainably removed, the quantity of residue that must be left on the field to maintain current soil organic matter (SOM_{min}) levels was first estimated. This SOM_{min} value is considered very crucial in determining the reasonable and safe amount of stover that may be removed without adversely impacting long-term soil health and productivity. The theory is that, for a particular climate, soil-type and cropping/eco-system, SOC levels will equilibrate between decomposition/mineralization (oxidization with evolution of carbon dioxide) and organic matter inputs to form SOM (Mann et al. 2002). Any adverse change in management practices, such as indiscriminate residue removal, will reduce carbon inputs, leading to a decrease in SOC, until a new equilibrium is reached (Follett 2001). Therefore the SOM_{min} is explicitly considered by recognizing the value of residue for maintaining current SOM/SOC levels. Erosion constraints to collection were considered implicitly - the logic being that the amount of residue left on the soil surface to satisfy sustainable soil quality requirements would adequately provide soil erosion mitigation requirements, since soil surface residue needed to maintain SOM is reported to be greater than that required to control erosion (Johnson et al. 2006; Wilhelm et al. 2007).

The following four assumptions were made in this section:

1) A typical healthy soil in Ontario has 3.0 % SOM in an acre of land in the plough layer of 15-18 cm (6-7 inches) containing 908,000kg (2,000,000 lbs) of soil (VandenBygaart et al. 2003). This would result in 67,200 kg SOM /ha (60,000 lb SOM/ac).
2) Carbon stored in the agricultural regions of Ontario is likely near, or at, a steady state (Campbell et al. 1991; Liang et al. 1998), a condition where the rate of carbon inputs would be almost equal to carbon outputs from loss through decomposition and other processes, such as leaching and erosion (Ellert and Gregorich 1996).
3) On average, microbes would decompose (mineralize) SOM at a rate of about 2-2.5% (average of 2.25%), using existing SOM as a food source (Kätterer et al. 1998). To elucidate the SOM mineralization rate in a typical Ontario soil, data obtained from an ongoing 22-year study conducted on a silt loam soil at Elora was used and this data revealed a 2.5% mineralization rate. This implies that an annual supply of 1,680 kg SOM/ha would be required in the Elora soil to maintain current SOM levels (i.e., 67,200kg SOM* 2.5%). The value would be 1,512kg SOM/ha (i.e., 67,200 kg SOM*2.25%), if the average mineralization rate of 2.25% found in the literature was used. To obtain the residue equivalent values, the rate at which SOM is formed from crop residue was first determined.
4) SOM formation rate (i.e., the rate of residue transformation to SOM) ranges between 10% and 20%, with an average of 15% (Angers et al. 1995; VandenBygaart et al. 2002; Murage and Voroney 2008). To verify the SOM formation rate in the Elora silt loam soil, the annual amount of SOM formed from carbon inputs was determined, revealing an average of 15.1%, a value that falls within the range given in the literature cited above. At this rate of SOM formation, different amounts of residue to maintain SOM levels would be required.

A summary of the impact of SOM decomposition/mineralization rates and SOM formation rates on the minimum amount of crop residue that should be left on the field is presented in Table 2.5.

Table 2.5: Estimated sustainable minimum residue required to maintain SOM levels (Res_{min}) [1]

	Mineralization Scenario		
Mineralization Rates of Existing SOM (%)	2	2.25	2.5
SOM_{min} (kg/ha)	1,344	1,512	1,680
Rate of SOM Formation [SOM_{form}] from Residue Input (%)	Res_{min} (kg/ha/yr)	Res_{min} (kg/ha/yr)	Res_{min} (kg/ha/yr)
10	13,440	15,120	**16,800**
15	8,960	**10,080**	11,200
15.1	8,901	10,013	**11,126**
20	**6,720**	7,560	8,400

[1]The calculated Res_{min} amounts are the sum of total above- and below-ground residue volumes

Table 2.5 shows the minimum amount of residue that should be retained, depending on the mineralization rate of existing SOM (SOM_{min}) and the rate at which new SOM is being formed (SOM_{form}). This table is used in further calculations and scenario establishment. Based on Table 2.5, the following scenarios were established:

1) A University of Guelph Elora Research Station **(ERS)** scenario defined by prevailing conditions in the Western Ontario geographical region and supported with data from a long-term rotation study; the SOM mineralization rate equals 2.5%, the SOM formation rate is 15.1%, and the minimum annual amount of crop residue to be retained in a rotation (Res_{min}) would be 11,126 kg residue/ha/yr.
2) If the rates were based on averages of SOM mineralization rate and SOM formation rate in published literature (i.e. **Literature means**) (2.25% and 15% respectively), 10,080 kg residue/ha/yr crop residue would be required to sustainably maintain SOM.
3) In the **best case** scenario, the quantity of crop residue to be retained would have the lowest SOM mineralization rate of 2% and the highest SOM formation rate of 20%. At these rates, the quantity of crop residue required to maintain minimum SOM levels would be 6,720 kg residue/ha/yr.
4) The **worst case** scenario would have the highest SOM mineralization rate of 2.5% and the lowest SOM formation rate of 10%. At these rates, the quantity of crop residue required to maintain minimum SOM levels would be 16,800 kg/ha/yr.

***Step 2**: Estimating above-ground residue from grain yield under a rotation system (i.e. above-ground residue less the grains)*

The potential above-ground post-harvest residue yields from 5-year average crop grain yields (2004-2008), harvest indices (or residue to grain ratios) and total production of crops in a rotation were estimated. It was assumed that corn, soybean and wheat crops are typically grown in rotation (e.g., corn-soybean and corn-soybean-wheat) in Ontario. Since OMAFRA grain production is reported in units of bushels/acre fresh grain weight, these values were converted into kg/ha on a dry weight basis, assuming the following for:

- Corn:
    - HI = 0.5 (residue to grain ratio is 1:1) (Tollenaar et al. 2004; Wilhelm et al. 2007; Wilcke and Wyatt 2002);
    - The conversion factor of a bushel of corn, 56 lb/bu to kg/bu= 62.71 (ASA-CSSA-SSSA SCI Journals Conversion Factors 2010); and
    - 15.5% moisture content;
- Soybean:
    - HI = 0.5 (Morrison et al. 1999; Kumudini et al. 2001; McDonald 2009);
    - The conversion factor of a bushel of soybean, 60 lb/bu to kg/bu = 67.19 (ASA-CSSA-SSSA SCI Journals Conversion Factors 2010); and
    - 13.0% moisture content; and
- Winter Wheat:
    - HI = 0.5 (Buyanovsky and Wagner 1986; McDonald 2009)
    - The conversion factor of a bushel of wheat 60 lb/ bu to kg/bu = 67.19 (ASA-CSSA-SSSA SCI Journals Conversion Factors 2010); and
    - 14.5% moisture content.

Harvest Index (HI) is equal to the amount of harvested grain (G) divided by the sum of the harvested grain and the above-ground Vegetative biomass (V). That is:

$$HI = [G/(G+V)] \qquad \text{(Equation 1)}$$

Since we assume HI = 0.5 for all three crop species, their residue-to-grain ratio=1.

Thus, for example, in Chatham-Kent:

Corn grain yield (kg/ha/yr) = corn grain yield (bu/ac/yr)*0.845*62.71

	= 161.8 (bu/ac/yr)*62.71 (kg/bu)*0.845
	= 8,573.77 kg/ha/yr
Corn stover biomass (kg/ha/yr)	= 1*8,573.77 (where 1=residue-to-grain ratio)
	= **8,573.77 kg/ha/yr**
Soybean grain yield (kg/ha/yr)	= soybean grain yield (bu/ac/yr)*0.87*67.19 kg/ha/yr
	= 44.0 (bu/ac/yr)*0.87*67.19
	= 2,572.03 kg/ha/yr
Soybean straw biomass (kg/ha/yr)	= 1*2572.03 (where 1=residue-to-grain ratio)
	= **2,572.03 kg/ha/yr**
Wheat grain yield (kg/ha/yr)	= wheat grain yield (bu/ac/yr)*1.56*0.855*67.19 kg/ha/yr
	= 79.8 (bu/ac/yr)*0.855*67.19
	= 4,584.30 kg/ha/yr
Wheat straw biomass (kg/ha/yr)	= 1*4,584.30 (where 1=residue-to-grain ratio)
	= **4,584.30 kg/ha/yr**

Step 3: Estimating below-ground root residue (including rhizodeposits), produced under a rotation system

The literature provides evidence that roots contribute substantial amounts of C to SOM (Gale and Cambardella 2000; Angers et al. 1995; Flesser et al. 2000). Root biomass (including rhizodeposits) was estimated by first determining the 'root to shoot ratio' (k_{rec}) as defined by Allmaras et al. (2004) and Wilts et al. (2004):

k_{rec} = [root biomass (R)]/[harvested grain (G) + Vegetative above-ground biomass (V)]

$$=R/(G+V) \qquad \text{(Equation 2)}$$

Rearranging Equation 2 provides the following relationship:

$$R = k_{rec} (G+V) \qquad \text{(Equation 3)}$$

where k_{rec} values for corn, soybean and winter wheat are given as 0.5, 0.6, and 0.8, respectively (Kuzyakov 2002a; Swinnen, et al. 199; Buyanovsky and Wagner 1987). Without the inclusion of rhizodeposits, the k_{rec} values are 0.37, 0.33 and 0.5, respectively, indicating the significant contribution of rhizodeposits in root SOM/SOC dynamics (Barber and Martin 1976).

Given that Equation 1 can be rearranged to: G+V = (G/HI), it follows that:

$R = k_{rec} (G/HI)$ (Equation 4)

Using Equation 4, the root biomass for corn, soybean and winter wheat are estimated as follows:

Corn root biomass (R_{corn}) = 1*G_{corn} (HI = k_{rec} = 0.5);

Soybean root biomass ($R_{soybean}$) = 1.2*$G_{soybean}$ (HI = 0.5 and k_{rec} = 0.6); and

Winter wheat root biomass (R_{wheat}) = 1.6*G_{wheat} (HI = 0.5 and k_{rec} = 0.8).

Using Chatham-Kent for illustration:

Total corn root biomass	= 1*8,573.77= 8,573.77kg/ha/yr
Total soybean root biomass	= 1.2*2,572.03 = 3,086.44 kg/ha/yr
Total winter wheat root biomass	= 1.6*4,584.30= 7,334.88 kg/ha/yr

Step 4: Estimating total crop residue (**below-ground** ***root and above-ground residue) in a rotation system***

Total estimated residue of a crop in a rotation is the sum of the below-ground root and above-ground vegetative residues. Using Chatham-Kent as an example:

Total corn residue [RC]	= [8,573.77 + 8,573.77]
	= 17,147.55 kg/ha/yr
Total soybean residue [RS]	= [2,572.03 + 3,086.44]
	= 5,658.47 kg/ha/yr
Total Winter wheat residue [RW]	= [4,584.30+ 7,334.88]
	=11,919.20 kg/ha/yr

In a two-year corn-soybean rotation, the estimated total residue yield is the average of the sum of soybean residue biomass (roots plus above-ground residue) in the previous year (YS_{t-1}) and the residue biomass of corn root and corn stover in the current year (YC_t). In corn-soybean-wheat rotations, the total amount of residue yield in a year is the three-year average residue yield of the three crops:

$R_{T(t)}$ (kg/ha/yr) = [$RS_{(t-2)}$ + $RW_{(t-1}$+ $RC_{(t)}$]/3 (Equation 5)

where $R_{T(t)}$ is the average total residue biomass (roots, including rhizodeposits, plus above-ground vegetative parts) of soybean, wheat, and corn; $RS_{(t-2)}$ is soybean biomass two years earlier in the rotation cycle (root and above-ground straw residue); $RW_{(t-1)}$ is wheat biomass the previous year (root and above-ground straw residue); and $RC_{(t)}$ is the corn biomass from the current year (root plus stover residue).

For example, using Chatham-Kent and assuming, total average crop residue yield in a C-S-W rotation:

$RT_{(t)]}$ = [17,147.55 + 5,658.47 + 11,919.20]/3 = 11,575 kg/ha/yr

The above calculation represents the average annual return of root and vegetative residue (i.e., non-grain portions) of the three crops in the C-S-W rotation for Chatham-Kent in a given year.

Step 5: Estimating county level crop residue availability in a rotation and the percentage land area from which residue may be removed

Estimates of county-level removable residues (SRR_{Cty}) are the annual averages that may be removed on a county basis after accounting for the minimum amount that should be left on the field to offset sustainability constraints (RES_{min}). That is:

SRR_{Cty} = [$R_{T(t)}$ - RES_{min}] (kg/ha/yr) (Equation 6)

In the case of Chatam-Kent with a $R_{T(t)}$ of 11,575 kg/ha/yr for a CSW rotation and an assumed RES_{min} of 11,126 kg/ha/yr, an average of 449 kg ha^{-1} (11,575-11,126) could annually be sustainably removed across all farmland in a CSW rotation. This calculation assumes that grain yields, and therefore residue produced in a county is the same on all farms; this assumption also implies that the amount of residue that can be removed is the same for all farms in a county. However, grain yields, and therefore residue production, are not the same for all farms within a county. This implies that counties with very low or even negative SRR_{Cty} values may actually have some higher yielding farms where residues may be sustainably removed. Similarly, counties with substantially high SRR_{Cty} may have lower yielding farms where residue removal would be detrimental to the maintenance of SOM. Therefore, accounting for the proportion of farms within each county that could participate in sustainable residue removal should provide a more accurate estimate of total amount of crop residues that can be removed.

The percent land area within a county from which residues may be removed (i.e. 'qualified lands') and the total SRR based on land area distribution for both CS and CSW rotation systems were calculated based on the following assumptions:

1) Total residue production for each rotation is assumed to follow a normal distribution with a coefficient of variation (CV) of 0.2 (20%. Both assumptions are based on overall farm enterprise crop yield data distributions by year and county for 2004-2008 obtained from AGRICORP, which is the crop insurance provider for the farmers of Ontario. Our assumption of a normal distribution is supported by 25th percentile, 50th percentile and 75th percentile values obtained from the Agricorp data which does not significantly deviate from predicted 25th percentile, 50th percentile and 75th percentile values based on the average and standard deviation of yields that were aggregated by year and county.

2) The minimum amount of residue required to financially justify harvest ($RES_{worthwhile}$) is set at 500 kg/ha/yr. For example, if 11,126 kg/ha/yr of residue is required to be left on the field to maintain SOM (i.e., RES_{min} = 11,126 kg/ha/yr) in Chatham-Kent, then it is assumed that only farms that produce over 11,626 kg/ha/yr (i.e., 11,126+500) would consider residue removal.

As an example, the use of equation 6 would suggest that no residue can be removed from Chatham-Kent under CSW rotation system under the Elora scenario (i.e. 11,575-11,126=449kg/ha) when the minimum worthwhile harvest threshold is assumed to be 500 kg/ha. However, more than half of the land will be producing residue quantities in excess of maintenance requirements with a significant proportion having residue production that is high enough for worthwhile residue harvests. Even when mean production is less than the maintenance threshold, some of the more productive farms will qualify for worthwhile residue removal. The assumption of normal distribution provides a probability (likelihood) for occurrences of the range of yield levels, and therefore the range of residue production levels, associated with each county. Equation 6 can be modified so that the weighted average of SRR_{Cty} can be calculated for the proportion of farms that have residue production that exceeds RES_{min} + $RES_{worthwhile}$, with the weighting based on probability of occurrence predicted from the normal distribution. The highest probability of occurrence is associated with residue production levels that are close to the average with the probability of occurrence declining as residue production levels become increasingly higher, and lower, than the average. Sustainable Removable Residue (SRR_{Cty}) from only lands that have high enough residue production levels (i.e. qualified) for a sustainable worthwhile harvest is based on a modification of Equation 6 and is calculated as follows:

$\sum$ ([$R_{T\,(t)}$ - RES_{min}] * probability of occurrence) for the range of annual residue production levels ($R_{T\,(t)}$) that exceeds $RES_{min} + RES_{worthwhile}$) Equation 7

Equation 7 is referred to as sustainably removable residue-truncated average (*SSRj*). In the case of Chatam-Kent with a minimum residue level for Elora conditions of RES_{min}=11,126 kg/ha and a county average residue supply from a CSW rotation ($E(TR_{CSW})$) of 11,575 kg/ha, 49% of the land area produces residue yields exceeding 11,626 (RES_{min}+500), and the average county residue yield is 1,143 kg/ha when weighted summation of sustainably removable residue is restricted to 49% of the qualified land area. The average residue yield on the qualified land area is 2,328 kg/ha (1,143/0.49). About 11% of the land area produces residue yields between 11,126 and 11,626 kg/ha and is not included given the assumption of an annual minimum economic harvest threshold of 500 kg/ha. The same procedure is employed to calculate the average county residue yield under CS rotation (the weighted summation of sustainably removable residue is restricted to 46% of the qualified land area); the average county residue yield is 1,033 kg/ha, and the average residue yield on the qualified land area is 2,245 kg/ha (1,033/0.46).

In addition to a distribution for yield, there is a distribution in land area allocated to the two cropping rotations. The area sown to each of the three crops is assumed to be the average of the five year period 2004 to 2008. The crop with the smallest area planted determined the land area devoted to the 3-year rotation. Using Chatham-Kent as an example, wheat is the crop with the lowest seeded area (A_W= 35,754 ha) and 90% of the wheat area is assumed to be in a 3-year rotation with corn (A_C= 52,683 ha) and soybeans (A_S = 90,769 ha). Thus, the area of each crop in the 3-year rotation is 32,179 ha ($ACSW_i$=0.9*35,754) and the total land area in the 3-year rotation for any given year is 96,536 ha (*ACSW*=3*32,179). Similarly, for the 2-year rotation, the crop (either corn or soybeans) with the least area was used to determine the land devoted to the 2-year rotation. Corn and soybean area potentially available for the 2-year rotation was calculated based on area estimates after removing the area assigned to the 3-year rotation. In the case of Chatham-Kent, where corn was the 2-year limiting crop with a total of 52,683 ha, it was assumed that 32,179 ha were in the 3-year rotation, which leaves 20,504 ha potentially available to be in a 2-year rotation. Again, if it is assumed that 90% of the remaining corn area is in a 2-year rotation with soybeans, then the land area of each crop in the 2-year corn-soybean rotation is 18,453 ha (ACS_i=0.9*32,179) and the total land area in the 2-year rotation is 36,907 ha (ACS=2*18,453). The area of crops not included in the 2-yr and 3-year rotations were calculated as the difference between the total area of the various crops produced in the county and the area estimated to be in the 2-yr and 3-yr rotations.

The product of county average removable residue (SRR_j) and the land area under the rotation types (A_j) provides the estimate of total residue yield from each county (TSRR_j)). For example, for Chatham Kent:

Total residue yield under CS rotation ($TSRR_{CS}$) =1033.1kg/ha*36,908 ha =38,130 t, and

Total residue yield under CSW rotation ($TSRR_{CSW}$) =1143 kg/ha*96,536 ha =110,340 t.

Total yearly residue from CS and CSW rotations ($TSRR$) is simply the sum of the annual amount from the two rotations ($TSRR$= $TSRR_{CS}$+$TSRR_{CSW}$= 38,130+110,340=148,470). Thus, 148,470 t of residue is the annual amount that can be sustainably collected from Chatham-Kent.

A summary of the Chatham-Kent County example running throughout this section, regarding the results of the 5-step approach described above, is illustrated in Table 2.6. The results of the statistical analysis are presented in Tables 2.7-2.10 and represent the four scenarios dictated by the selected RES_{min} values.

Table 2.6: Estimated annual sustainably removable biomass residue from qualified lands in Chatham-Kent County by the 5-step approach described in Section 2.5 for CS and CSW

Cropping System	CS	CSW
CORN		
Average harvested area of CORN in Chatham-Kent [5-year average: 2004-2008] (ha/yr)	51,394.50	51,394.50
Average Corn Grain Yield [5-year average: 2004-2008] (bu/ac)	161.8	161.8
Average Corn Grain Yield @ 15% Moisture; bu/ac = 62.7kg/ha (kg/ha/yr)	8,573.77	8,573.77
Average Corn Stover Biomass Yield [Harvest Index (HI) = 0.5] (kg/ha/yr)	8,573.77	8,573.77
Corn Root Biomass Yield (kg/ha/yr)	8,573.77	8,573.77
Total Average Corn Root and Stover Biomass (kg/ha/yr)	17,147.55	17,147.55
SOYBEAN		
Average harvested area of SOYBEAN in Chatham-Kent [5-year average: 2004-2008] (ha/yr)	90,387.90	90,387.90
Average Soybean Grain Yield [5-year average: 2004-2008] (bu/ac)	44	44
Average Soybean Grain Yield @ 13% Moisture; bu/ac = 67.19 kg/ha (kg/ha/yr))	2,572.03	2,572.03
Average Soybean Straw Biomass Yield [Harvest Index (HI) = 0.5] (kg/ha/yr)	2,572.03	2,572.03
Soybean Root Biomass (kg/ha/yr))	3,086.44	3,086.44
Total Soybean Root and Straw Biomass (kg/ha/yr)	5,658.47	5,658.47
WINTER WHEAT		
Average harvested area of WINTER WHEAT in Chatham-Kent [5-year average: 2004-2008] (ha/yr)		29,972.59
Average Winter Wheat Grain Yield [5-year average: 2004-2008] (bu/ac)		79.8
Average Winter Wheat Grain Yield @ 14.5% Moisture; bu/ac = 67.19 kg/ha (kg/ha/yr))		4,584.88
Average Winter Wheat Straw Biomass Yield [Harvest Index (HI) =0.5] (kg/ha/yr)		4,584.88
Winter Wheat Root Biomass (kg/ha/yr))		7,334.88
Total Winter Wheat Root and Straw Biomass (kg/ha/yr)		11,919.18
COMBINED RESIDUE YIELDS IN ROTATIONS Total Average Crop Residue Yield in a Rotation [RT(t)] (kg/ha/yr)	11,403	11,575
Sustainable minimum residue required to maintain SOM levels (Res_{min} in rotation [RES_{min}] (kg/ha/yr)	11,126	11,126
Sustainable Average County Yield (SSRCty) **[See Eq. 7]** (kg/ha/yr)	1,033	1,143
Percentage land area in Chatham-Kent from which residue may be sustainably removed [i.e. ‘qualified’ land area within Chatham-Kent] (%)	46	49
Total residue yield from CS rotation system [SSRCty *Total land area in CS] (t/yr). [Land area in CS=36,908 ha]	38,130	
Total residue yield from CSW rotation system [SSRCty *Total land area in CSW] (t/yr). [Land area in CSS=96,536 ha]		110,340
Total crop residue yield from both CS and CSW systems in Chatham-Kent (t/yr)		**148,470**

Table 2.7: Estimated sustainably available crop residues in the Best-case Scenario (RES_{min}=6,270kg/ha)

County/Division	Corn-Soybean Rotation: Average SRR (kg/ha/yr)	Corn-Soybean Rotation: Qualified Land Area (%)	Corn-Soybean-Wheat Rotation: Average SRR (kg/ha/yr)	Corn-Soybean-Wheat Rotation: Qualified Land Area (%)	Total SRR based on land area distribution under rotation types (tDM/yr)
Brant	3203.1	91.1	3387.5	92.2	110,576
Chatham-Kent	4696.4	96.7	4865.7	97.0	643,053
Elgin	3883.1	94.4	4145.6	95.3	337,759
Essex	3370.9	92.1	3636.2	93.4	191,086
Haldimand-Norfolk	2819.0	88.4	2784.3	88.1	188,950
Hamilton	2739.9	87.8	2836.9	88.6	55,880
Lambton	4168.7	95.4	4386.6	96.0	496,615
Middlesex	4237.1	95.5	4639.1	96.5	630,292
Niagara Regional	2245.4	82.6	2130.2	81.1	55,610
Oxford	4472.3	96.2	4983.8	97.2	342,857
Southern Ontario	**3928.7**	**94.5**	**5024.2**	**98.9**	**3,052,678**
Bruce	2806.1	88.3	4382.6	97.7	215,445
Dufferin	2069.8	80.2	3477.1	94.3	38,693
Grey	1985.5	79.0	3181.8	92.4	42,089
Halton	1480.3	69.5	2469.5	84.4	27,066
Huron	4034.5	94.9	5431.0	99.2	777,350
Peel	2039.0	79.8	3136.6	92.1	25,303
Perth County	4134.9	95.2	5750.4	99.4	555,589
Simcoe	2294.3	83.2	3539.4	94.7	176,463
Waterloo	2959.1	89.5	4234.7	97.4	136,144
Wellington	2686.8	87.3	4155.2	97.2	246,027
Western Ontario	**3295.8**	**91.7**	**4701.4**	**98.4**	**2,240,169**
Durham	2129.5	81.1	3070.1	91.7	100,915
Hastings	1594.1	72.0	2334.4	82.7	17,162
Kawartha Lakes	1569.0	71.5	2418.4	83.9	40,065
Northumberland	2310.2	83.4	3113.3	92.2	67,192
Peterborough	1210.6	62.7	1843.1	72.0	14,505
Prince Edward	1799.1	75.9	2651.8	87.3	33,106
York	1795.8	75.8	2696.9	87.8	47,601
Central Ontario	**1913.0**	**77.8**	**2754.1**	**88.6**	**320,546**
Frontenac	2166.0	81.5	2518.8	86.3	7,287
Lanark	2437.7	84.8	2168.4	81.8	10,986
Leeds & Grenville	2474.9	85.2	2804.4	89.8	26,776
Lennox & Addington	1491.3	69.8	2136.0	79.0	14,046
Ottawa	3756.6	93.9	3959.8	97.0	114,711
Prescott & Russell	3678.2	93.6	3392.6	94.9	141,454
Renfrew	2229.6	82.4	2841.7	89.9	11,490
Stormont, Dundas	3923.0	94.5	4444.3	98.1	249,970
Eastern Ontario	**3525.9**	**92.9**	**3642.1**	**95.8**	**576,720**
ONTARIO TOTAL					***6,190,113***

Best-case Scenario (Table 2.7)

This scenario is constructed by using the lowest SOM Mineralization Rate (SOM_{min} = 2.0%), the highest SOM Formation Rate (SOM_{form} = 20%) and an annual Minimum Residue to Retain (Res_{min}) of 6,720 kg/ha/yr. County averages for sustainable residue removal (SRR_{Cty}) vary across geographical regions, among counties in a region, and between rotation types. For example, Southern Ontario provided the highest average SRR_{Cty} under both CS and CSW systems compared to other regions. Oxford County produced the highest SRR_{Cty} from the rotation systems among all counties. It is worth noting that, in general, SRR_{Cty} values for CSW are greater than those for CS systems, except in the case of Lanark, and Prescott and Russell in the Eastern region, where the reverse is true. The outperformance of CS over CSW systems in Lanark, and Prescott and Russell could be attributed to the lower yields of wheat in those areas. This trend has been consistent under all scenarios. In general, therefore, the complexity of rotation seems to enhance residue production and, subsequently, the amount that can be sustainably removed.

Compared to the other three regions, percent qualified land area is highest in counties in the Southern region under both CS and CSW systems. For example, percent qualified land ranges between 82% in Niagara Region and 97% in Chatham-Kent in a 2-year rotation scheme; under a 3-year CSW system, the percent qualified land area remains the same (97%). In general, the percentage land from which residue could be sustainably removed is lowest in the Central region.

Given the assumptions made in the calculations, a total of about 6.2 million tonnes of residue may be sustainably removed annually in the entire province from the two rotation systems under this scenario (Table 2.7). Annual residue amounts removable from the Southern, Western, Central and Eastern regions are 3.1, 2.2, 0.33, and 0.58 million tonnes, respectively. It is, however, not likely that such an optimal scenario is attainable under Ontario conditions, other than from exceptionally well-managed farms. Actual amounts of residue collected could also be lower due to technical harvest constraints.

Table 2.8: Estimated sustainably available crop residues in the Literature Average Scenario (RES_{min}=10,080kg/ha/yr)

County/Division	Corn-Soybean Rotation Average SRR (kg/ha/yr)	Corn-Soybean Rotation Qualified Land Area (%)	Corn-Soybean-Wheat Rotation Average SRR (kg/ha/yr)	Corn-Soybean-Wheat Rotation Qualified Land Area (%)	Total SRR based on land area distribution under rotation types (tDM/yr)
Brant	671.6	36.3	777.5	40.1	24,193
Chatham-Kent	1700.3	64.1	1837.7	66.6	240,166
Elgin	1094.7	50.0	1280.2	54.9	99,973
Essex	767.5	39.8	931.1	45.2	48,613
Haldimand-Norfolk	475.1	28.3	458.8	27.6	31,505
Hamilton	438.8	26.7	483.3	28.7	9,203
Lambton	1296.5	55.3	1458.8	59.1	164,520
Middlesex	1347.3	56.6	1655.3	63.2	216,429
Niagara Regional	246.8	17.0	210.7	15.0	5,699
Oxford	1524.6	60.6	1934.7	68.3	127,490
Southern Ontario	**1126.3**	**50.9**	**1968.0**	**68.9**	**967,791**
Bruce	469.0	28.0	1455.7	59.1	63,217
Dufferin	193.2	14.0	831.1	42.0	9,033
Grey	170.3	12.6	659.6	35.9	7,467
Halton	67.6	5.7	326.1	21.3	3,173
Huron	1200.5	52.9	2314.1	74.0	298,102
Peel	184.7	13.5	635.2	34.9	4,574
Perth County	1272.0	54.7	2595.0	77.5	225,876
Simcoe	263.0	17.9	869.5	43.2	40,467
Waterloo	542.7	31.2	1345.2	56.5	36,393
Wellington	415.1	25.6	1287.2	55.1	69,509
Western Ontario	**723.7**	**38.2**	**1704.9**	**64.2**	**757,811**
Durham	210.5	15.0	599.8	33.5	16,977
Hastings	85.7	7.0	276.8	18.7	1,692
Kawartha Lakes	81.5	6.7	307.1	20.3	4,728
Northumberland	268.5	18.2	622.6	34.4	11,289
Peterborough	35.1	3.2	135.4	10.4	915
Prince Edward	125.5	9.7	400.2	24.9	4,627
York	124.8	9.7	419.5	25.8	5,789
Central Ontario	**151.8**	**11.4**	**445.2**	**27.0**	**46,017**
Frontenac	221.7	15.6	345.4	22.2	808
Lanark	314.3	20.6	222.4	15.7	1,373
Leeds & Grenville	328.4	21.4	468.3	28.0	3,588
Lennox & Addington	69.2	5.8	212.6	15.1	1,316
Ottawa	1009.1	47.6	1147.7	51.5	30,876
Prescott & Russell	957.8	46.0	780.5	40.2	36,772
Renfrew	241.6	16.7	485.5	28.8	1,504
Stormont, Dundas	1121.9	50.8	1503.6	60.1	71,946
Eastern Ontario	**861.5**	**43.0**	**934.8**	**45.3**	**148,183**
ONTARIO TOTAL					***1,919,802***

Literature Average Scenario (Table 2.8)

This scenario is created by conditions with average SOM_{min} and SOM_{form} values reported in the literature, where SOM_{min} = 2.25%; SOM_{form} = 15%; and estimated Res_{min} = 10,080 kg/ha/yr. These values would be dependent on soil types, land topography and climatic conditions that influence crop yield, SOM_{min} and SOM_{form}, and, therefore, represent a wide range of conditions. In general, the average SRR per county (SRR_{Cty}) is highest in the Southern region under both CS and CSW systems. Values from Table 2.8 indicate variability of percent qualified land area among counties and among the geographic regions of Ontario. Counties in the Central Region have very low percent qualified land area, with values as low as 3% in Peterborough and 7% in Kawartha Lakes under CS rotation system. Percentage land area from which residue could be sustainably removed is highest in counties within Southern Ontario. For example, Oxford County has more than 60% qualified land under both CS and CSW systems and about 60% of the counties in Southern Ontario have at least 40% eligible land for residue removal.

Under this scenario, a total of about 1.9 million tonnes of residue may be sustainably removed annually in the entire province under the two rotation systems. Annual residue amounts removable from the Southern, Western, Central and Eastern regions are 0.97, 0.76, 0.046, and 0.15 million tonnes, respectively. Considering that this scenario emerged from average conditions in the literature, it is likely that a high proportion of farms in Ontario could be in this category.

Table 2.9: Sustainably available crop residues in the Elora Scenario (RES_{min}=11,126kg/ha/yr)

County/Division	Corn-Soybean Rotation Average SRR ((kg/ha/yr)	Corn-Soybean Rotation Qualified Land Area (%)	Corn-Soybean-Wheat Rotation Average SRR (kg/ha/yr)	Corn-Soybean-Wheat Rotation Qualified Land Area (%)	Total SRR based on land area distribution under rotation types (tDM/yr)
Brant	300.8	19.0	366.1	22	11,103
Chatham-Kent	1033.1	46.1	1143.5	49	148,470
Elgin	577.8	31.1	711.2	36	54,284
Essex	359.7	21.8	465.8	27	24,240
Haldimand-Norfolk	188.8	13.0	180.2	13	12,450
Hamilton	169.7	11.9	193.2	13	3,614
Lambton	723.2	36.4	844.9	40	95,091
Middlesex	760.9	37.7	997.5	45	127,799
Niagara Regional	78.0	6.2	63.0	5	1,738
Oxford	895.5	42.1	1222.6	51	78,764
Southern Ontario	**600.1**	**31.9**	**1250.0**	**52**	**557,606**
Bruce	185.6	12.8	842.5	40	35,042
Dufferin	56.0	4.6	400.2	24	4,323
Grey	47.2	4.0	293.6	19	3,174
Halton	13.5	1.3	113.7	9	1,074
Huron	653.2	33.9	1541.2	58	189,184
Peel	52.7	4.4	279.1	18	1,941
Perth County	705.1	35.8	1784.8	63	148,253
Simcoe	85.0	6.6	425.1	25	19,366
Waterloo	225.8	15.1	759.3	38	19,153
Wellington	157.4	11.2	716.3	36	37,500
Western Ontario	**332.5**	**20.5**	**1036.8**	**46**	**459,011**
Durham	62.9	5.1	258.4	17	6,944
Hastings	18.6	1.7	91.1	7	525
Kawartha Lakes	17.4	1.6	104.8	8	1,582
Northumberland	87.4	6.8	271.7	17	4,596
Peterborough	5.6	0.6	34.6	3	225
Prince Edward	31.2	2.7	149.8	11	1,693
York	31.0	2.7	159.7	11	2,031
Central Ontario	**40.4**	**3.5**	**173.0**	**12**	**17,595**
Frontenac	67.5	5.4	122.8	9	258
Lanark	108.1	8.2	67.7	5	466
Leeds & Grenville	114.8	8.6	185.2	13	1,262
Lennox & Addington	14.0	1.3	63.7	5	388
Ottawa	518.5	28.7	615.3	33	15,883
Prescott & Russell	483.7	27.3	367.9	22	18,554
Renfrew	75.8	6.0	194.4	13	533
Stormont, Dundas	597.0	31.8	879.3	42	38,440
Eastern Ontario	**419.9**	**24.5**	**468.2**	**27**	**75,784**
ONTARIO TOTAL					***1,109,996***

Elora Scenario (Table 2.9)

The Elora scenario is defined by prevailing conditions in the Western Ontario geographical region and, probably, most parts of the Southern and Eastern regions of the province, although site-specific variations would exist because of topographic and soil-type differences. Data on SOM_{min} and SOM_{form} were obtained from a silt loam soil at the University of Guelph Research Station at Elora (ERS), Wellington County, where SOM_{min} = 2.5%, SOM_{form} = 15.1% and estimated Res_{min} = 11,126 kg/ha/yr. On a county and regional basis, the results suggest that CSW rotations favour more residue removal compared to CS (except in the case of Eastern Ontario). For example, average SRR values are 1,250, 1,037 and 173 kg/ha/yr under CSW, and 600, 332 and 40 kg/ha/yr under CS for the Southern, Western and Central regions, respectively. The latter results strongly suggest that, in Southern, Western and Central Ontario, CSW systems double SRR volumes compared to CS systems. Percentage qualified lands for residue removal range between 7% and 67% in Southern Ontario counties and between 1% and 60% in counties in Eastern Ontario.

Under the Elora scenario, about 1.1 million tonnes of residue may be sustainably removed annually in the entire province under the two rotation system. Annual SRR from the Southern, Western, Central and Eastern regions are 0.56, 0.46, 0.02, and 0.075 million tonnes, respectively. Since this scenario is created from actual field observations, the results may be considered more practical and, therefore, applicable to individual farms with similar conditions in the province.

Table 2.10: Sustainably available crop residues in the Worst-case Scenario (RES=16,800kg/ha/yr)

County/Division	Corn-Soybean Rotation: Average SRR (kg/ha/yr)	Corn-Soybean Rotation: Qualified Land Area (%)	Corn-Soybean-Wheat Rotation: Average SRR (kg/ha/yr)	Corn-Soybean-Wheat Rotation: Qualified Land Area (%)	Total SRR based on land area distribution under rotation types (tDM/yr)
Brant	0.04	0.006	0.11	0.014	1
Chatham-Kent	5.79	0.483	8.26	0.668	797
Elgin	0.72	0.072	1.54	0.144	66
Essex	0.10	0.013	0.31	0.034	15
Haldimand-Norfolk	0.00	0.000	0.00	0.000	0
Hamilton	0.00	0.000	0.00	0.000	0
Lambton	1.64	0.152	2.86	0.253	304
Middlesex	1.97	0.180	5.13	0.433	456
Niagara Regional	0.00	0.000	0.00	0.000	0
Oxford	3.51	0.305	10.40	0.824	468
Southern Ontario	**0.83**	**0.082**	**11.22**	**0.883**	**2,107**
Bruce	0.00	0.000	2.83	0.251	106
Dufferin	0.00	0.000	0.17	0.019	2
Grey	0.00	0.000	0.04	0.005	0
Halton	0.00	0.000	0.00	0.000	0
Huron	1.13	0.109	22.99	1.685	2,200
Peel	0.00	0.000	0.03	0.004	0
Perth County	1.49	0.140	37.76	2.620	2,513
Simcoe	0.00	0.000	0.21	0.024	9
Waterloo	0.00	0.000	1.95	0.179	39
Wellington	0.00	0.000	1.58	0.148	77
Western Ontario	**0.07**	**0.009**	**5.87**	**0.490**	**4,946**
Durham	0.00	0.000	0.01	0.002	0
Hastings	0.00	0.000	0.00	0.000	0
Kawartha Lakes	0.00	0.000	0.00	0.000	0
Northumberland	0.00	0.000	0.02	0.003	0
Peterborough	0.00	0.000	0.00	0.000	0
Prince Edward	0.00	0.000	0.00	0.000	0
York	0.00	0.000	0.00	0.000	0
Central Ontario	**0.00**	**0.000**	**0.00**	**0.000**	**0**
Frontenac	0.00	0.000	0.00	0.000	0
Lanark	0.00	0.000	0.00	0.000	0
Leeds & Grenville	0.00	0.000	0.00	0.000	0
Lennox & Addington	0.00	0.000	0.00	0.000	0
Ottawa	0.48	0.050	0.91	0.089	1
Prescott & Russell	0.36	0.039	0.11	0.014	0
Renfrew	0.00	0.000	0.00	0.000	0
Stormont, Dundas	0.81	0.080	3.29	0.288	7
Eastern Ontario	**0.20**	**0.023**	**0.32**	**0.035**	**8**
ONTARIO TOTAL					***7,053***

Worst Case Scenario (Table 2.10)

This scenario is defined by a high SOM_{min} of 2.5%, a low SOM_{form} of only 10% and an estimated Res_{min} = 16,800 kg/ha/yr. Under this scenario and under the assumptions made, no cropping system could provide enough residues to offset Res_{min}, except in qualified lands in Chatham-Kent, Elgin, Middlesex, Oxford, Huron and Perth counties, where very low amounts of residue could be removed. Under this scenario, only about 7,000 tonnes of residue may be sustainably available for collection annually in the entire province. Such a scenario may exist in locations/farms with very low SOM content (e.g., sandy soils) or with highly eroded soils.

OPG's suggested 2 million tDM of biomass could easily be obtained from crop residues alone, providing that the best-case scenario were true. However, as long as the more marginal scenarios were closer to the actual situation, crop residue biomass would likely need to be supplemented by dedicated crops, such as switchgrass or Miscanthus, as discussed in Section 4. If the worst-case scenario applied predominantly to Ontario, then crop residues would not provide a viable source of biomass for heat or electricity generation. There are comparatively minor differences in the assumptions leading to the four scenarios, but the results differ greatly, indicating a need for further physical research. Of course, the economics of removing these residues may be prohibitive, even if some residues could be sustainably removed.

Since estimates of SRR depend on total biomass yield, one would expect an increase in grain yield of the selected crops in rotation to result in increases in SRR due to increases in the number of qualified lands from which residue can be removed and increases in residue amounts that can be removed from existing qualified lands. The extent of the increases would depend on the scenario type developed in this study. For example, using the above five-step approach and assuming that harvest index (HI) and root: shoot ratio remain constant, a 20% increase in grain yield of each of the three crops would result in a 25% increase in SRR for the best case scenario and a 167% increase for the Elora scenario, across Ontario. The impact of grain yield changes as well as the baseline SOC on SRR warrants further study.

2.6 Break-even Analysis of Removable Crop Residues

There is currently no market price for residue biomass in Ontario. As a result, we used break-even analysis as an appropriate method to consider the financial feasibility of crop residue biomass as a bioenergy feedstock. Farmers should not even consider supplying crop residues to the 'aggregator' or power plant unless they are able to at least break even on the sale of the residue. The price offered for the residues for biomass production must overcome the opportunity cost, which is determined by the next most valuable price offered for the product. In the case of wheat straw, this may be the price of straw for animal bedding, or any of the other alternate uses presented in Table 2.4. However, in this analysis, the agricultural opportunity costs were assumed to be zero. This implies that all other opportunities either do not break even, or just break even. In order words, other uses of the soil/land will gain zero profit. In this case, a reasonable break-even price for crop residues considers the harvest, transport and storage costs, along with the replacement value of the nutrients removed during harvest. The replacement value of nitrogen, phosphorus and potassium (N-P-K) is determined by the market cost of restoring these nutrient levels with fertilizers. At the farm-gate level, costs of harvesting residues include all resources associated with collection, baling, transportation and storage until they are transported to 'aggregation facilities'. The current prevailing costs are obtainable from OMAFRA and other sources.

When crop residue is harvested, plant nutrients are removed and become unavailable to the subsequent year's crop. Therefore, a potential cost to the farmer is replacing these nutrients, in order to maintain crop production levels (Petrolia 2006). For example, the nutrient value of corn stover would be affected by the type of corn hybrid, soil fertility level, growing conditions and residue harvest date. Collectively, these parameters would impact the amount of nutrients in the stover. Crop nutrients of interest in this study are nitrogen (N), phosphorus (P), and potassium (K) although the impact on micro nutrients should be born in mind. In cropping systems where soybeans follow corn (e.g. corn-soybean), nitrogen does not need to be replaced (Petrolia, 2006). The estimated net value of residue is the product of the average amount of nutrients in residue ($/tonne) and the fertilizer value of the nutrients contained in residue ($/kg):

$$NV = FC*NiR \qquad \text{Equation 8}$$

where, NV is the estimated net value of residue ($/t), FC is the cost of Fertilizer ($/kg) and NiR is the average amount of nutrients in the residue (kg/t). Table 2.12 contains nutrient and cost information for each of the residues of interest.

Table 2.12: Summary of nutrient value and cost for corn stover, corn cobs, soybean straw and wheat straw.

Nutrient	**Average Nutrient Amount [NiR] (kg/t)**				**Cost of Fertilizer [FC] ($/kg)**	
	Corn Stover[b]	Corn Cobs[b]	Soybean Straw[c]	Wheat Straw[d]	2008 (High)[a]	2010 (Low)[e]
N	9.6	4.6	21.7	4.8	1.72	1.18
P_2O_5	2.1	0.8	2.2	1.6	2.07	0.84
K_2O	15.8	9.5	0.8	15.9	1.48	1.22

[a]Stewart and McDonald 2008
[b]NRC 1981
[c]http://extension.agron.iastate.edu/soybean/production_soilfert.html
[d]http://bulletin.ipm.illinois.edu/article.php?id=990
[e]OMAFRA 2010.

In addition to the nutrient replacement costs the break-even price estimate also involves the costs of crop residue harvest operations, including some or all of chopping, raking, baling, and storage. There may be different types of baling, but, in this analysis, the use of a round baler is assumed. Table 2.13 contains a summary of the harvest and storage costs ($/t) involved in crop residue procurement and also presents the resulting break-even price, when combined with the information in Table 2.12.

Table 2.13: Estimates of residue harvest and storage costs using custom rates in Ontario.

Operation	**Cost ($/t)**		
	Corn Stover	Soybean Straw	Wheat Straw
Chopping	4.83	0.00	0.00
Bailing	22.05	22.05	22.05
Field Removal	5.50	5.50	5.50
Storage	4.00	4.00	4.00
Total Harvesting Cost[a]	36.38	31.55	31.55
Total Nutrient Cost @ 2008 Prices	44.18	42.86	34.93
Total Nutrient Cost @ 2010 Prices	32.36	28.30	26.32
Break-Even Price @ 2008 Prices	80.56	74.41	66.48
Break-Even Price @ 2010 Prices	68.74	59.85	57.87

[a]Stewart and McDonald 2008

The break-even price for a residue is the price a farmer must receive in order to recover all of the direct costs associated with collecting the residue. In this analysis, as shown in Table 2.13, the break-even price is the sum of the harvesting and replacement nutrient cost. Values reported in the literature range between $57.00 and $80.00/t (Petrolia, 2006). The estimated price per tonne break-even value for crop residues in Ontario fall basically within this range. Corn stover has a higher break-even price because harvesting costs and nutrient replacement values are higher. Soybean straw has a higher nitrogen value than wheat straw, despite similar harvesting costs, implying a higher break-even price when N is more expensive. However, when K is more expensive, soybean straw break-even prices become much closer to those of wheat straw.

2.7 Conclusions and Recommendations

The most important challenges that determine expanded residue removal from Ontario fields revolve around sustainability issues. In this analysis, SOM, the major constraint that impacts ecosystem services such as resistance to soil erosion and crusting, soil aggregation and cation exchange capacity (CEC), was given priority. Estimates of the amount of crop residue that can be reasonably removed, on a commercial basis, while maintaining current SOM levels, can be made using knowledge of current SOM levels, the rate at which SOM is formed from above and below-ground biomass produced in a rotation, and the rate at which existing SOM is mineralized or decomposed. Based on this knowledge, a five-step approach was developed to estimate sustainably removable residue values (SRR) in typical Ontario soils. Unlike other methods, this approach is capable of handling any rotation type, and provides a basis for developing models and decision aids for SRR in the future. Both above- and below-ground residue yields are the drivers that determine carbon input levels in SOM formation. In particular, root biomass is very essential in adding quality residue to a rotation and should, therefore, be included in any efforts to quantify SOM formation.

The analysis presented in this section suggests that the possibility of crop residue removal in Ontario is feasible and worth the effort in only limited locations, which are referred to as ‘qualified lands’. Any indiscriminate removal in ‘unqualified’ lands would most likely lead to long-term adverse effects on essential ecosystem services provided by soils and would constitute unsustainable residue removal. To be sustainable, residue removal must only be practiced when essential soil ecosystem services and soil quality will not be compromised. Assuming the conditions in Ontario range between the worst-case scenario and the best-case scenario detailed previously, 7,053 kg to 6.2 million tonnes of residue could be removed annually across the province (Table 2.11). If the Elora field conditions, which could represent the most realistic estimate for most parts of the province, hold true, then approximately 1.1 million metric tonnes of sustainably removable residue per annum is available although harvestability limitations and constraints would reduce the volume feasibly attainable. This fails to meet the 2 million Mg/ha/year required by OPG. Assuming that the combined total residue production from corn, soybean and winter wheat was about 9.7 million metric tonnes for the entire province (Stewart and McDonald 2008), only 11% of total biomass residue may be sustainably removed from the combined rotation systems. Even if all residue removal were to occur under the best case scenario, considering all the assumptions made, only about 64% of the 9.7 million tonnes could be sustainably removed. Annual removal may, however, actually fall between the scenario values, depending on soil type, topography, climatic conditions and crop yield. The Southern and Western geographic regions of Ontario are most likely to provide over 90% of the residue, as a majority of the Classes 1 and 2 lands in the province are found in these two regions.

In order to increase carbon inputs and enhance the sustainability of residue removal with respect to quantity and eligible land area, more sources of carbon inputs would be required in the rotation systems. In general, it appears that the complexity of a crop rotation may be the most crucial management practice to encourage in the province, as it influences carbon inputs in the soil and, therefore, the amount of residue that may be sustainably removed. For example, except for some counties in the Eastern region, all other counties exhibited more average SRR_{Cty} under CSW compared to CS systems. Other management practices that would increase soil carbon inputs and help reduce soil erosion include the addition of cover and/or forage crops with prolific rooting systems and vegetative growth in rotations, adding animal manure or compost, and adding soil amendments that can increase both the active and heavy fractions of SOM. Implementing production systems that include no-till and contour cropping can also help to mitigate the adverse effects of residue biomass removal on soil quality and productivity.

Both the short and long-term effects of residue removal on soil properties and environmental quality need to be researched more vigorously, as it is essential that these effects be carefully weighed on a site-specific basis when making a determination about residue removal. Routine soil tests on individual farms need to include assessment of SOM formation and mineralization rates. Also, research on additional sources of soil organic matter, such as cover crops, must be pursued. To enhance the development of the biomass industry in Ontario, these research results would need to be applied to the development of decision-making tools for on-farm application.

Our break-even analysis indicates that farmers must receive an average of about $62.00/t residue in order to recover all of the direct costs associated with harvesting crop residue. These break-even prices represent an estimated minimum price necessary to cover all variable and fixed costs for the farmer and should not be construed as biomass price. Also, these prices do not ensure that biomass will be supplied; the actual market price needed to motivate farmers to supply crop biomass must be over and above the break-even prices. Potential economic trade-offs to residue removal would include competing uses of residue and higher fertilizer costs. A variety of commercial uses for crop residues are in various stages of development. For example, crop residues can be used as a feedstock for composite products, such as fiberboard, paper, and liquid fuels. Increases in demand for residue biomass would most likely result in higher prices for suppliers. If costs of fertilizers were to rise, the average break-even price would rise and less residue would likely be removed. If, however, costs of harvesting biomass were to be reduced through advances in harvesting technologies, the break-even price would fall.

SECTION 3: ESTIMATED AVAILABILITY OF CORN COB BIOMASS

Separate from the other parts of corn stover, corn cobs are considered to be a particularly viable potential source of biomass due to their unique physical characteristics. Corn cobs have more consistent density and less moisture than corn residue. The purpose of this section is to assess the availability of corn cobs, apart from stover, for use in energy and heat generation in Ontario. The specific objectives include, in the order that they are presented in the following text, an examination of corn cobs, the methods to acquire them, difficulties in their procurement, competing uses, an assessment of their availability in Ontario, and a break-even price analysis.

3.1 Description of Corn Cobs and their Relation to Grain Corn Production.

The corn cob is the central core of the corn ear and it is the most dense stover component (Hoskinson et al. 2007). Studies on corn stover composition found that corn cobs make up 15-20% of the total (Sokhansanj et al. 2006; Hanway 2007, Varvel and Wilhelm 2008). Pordesimo et al. (2004) reported that 15% of the stover dry mass is cob and that stalks (plus leaf sheaths and tassel), leaf blades, and husks (plus shank) accounted for 51%, 21%, and 13% of the stover, respectively. In this analysis, the cob to stover ratio was assumed to be 0.16 because this value represents an aggregate mean of several locations, over several years, as reported by Halvorson and Johnson (2009). The latter researchers reported this consistent relationship between cob and stover when N fertilizer was applied at rates sufficient to optimize grain yields in all cropping systems and hybrids. We also assumed that almost all (90% of cobs) may be sustainably removed from the field without adversely affecting soil quality or erosion control (Hanway 2007). The low nutrient content of corn cobs adds to its potential sustainable use as a biomass feedstock as the amount of nutrients, particularly N, but also P and K, removed with the cobs at harvest, which would later need to be replaced to maintain soil nutrient levels, is very minimal. This lack of nutrients also adds to the corn cob's combustion quality for heat and electricity generation. The low nutrient content of corn cobs results in a much lower cost of macro-nutrient replacement when compared to grain and stover (Table 2.12) and this allows for greater profit potential in feedstock collection. The profit potential becomes more significant as fertilizer prices increase.

3.2 Current Corn Cob Procurement and Storage Methods

Unlike corn stalk/stover, corn cobs tend to be drier at harvest (about 20% moisture) and have the highest energy density among stover components (Table 2.2). Corn cob collection methods may contribute to the viability of their use as biomass feedstocks. Currently, there are three known types of cob collection systems in North America. The first is the "grain-cob mix collection" method, where both cobs and grain first end up in the combine grain tank. Grain is later separated into a wagon or truck and cobs are piled on the ground to be collected afterward. While this method uses existing combines with small modifications to the grain/cob separator, it requires special separation equipment to later separate cobs from grain and an extra step to retrieve cobs from the ground. The grain-cob mix collection method is however not commonly used in Ontario. The "whole cob collection" method involves normal combine operation with a cob cart or wagon towed behind. With the straw chopper and spreader disengaged, grain goes into the tank and the rest goes onto a conveyor on a towed cart. Cobs and stover are then separated, with cobs going into the cart and stover back on the field. While this allows the farmer to easily transfer cobs to a wagon during harvest, it requires installation of in-cab controls and an approved hitch. The third approach involves adding a cob-collection device on the back of the combine so that grain and cobs are harvested in two separate streams. This method is considered the most efficient of the three.

3.3 Constraints and Limitations in Corn Cob Procurement

The most important limitation and challenge in harvesting and storing corn cobs is the initial moisture content at harvest. Corn cobs are generally harvested with moisture content in the range of 20-50%, which depends on the corn cultivar characteristics and harvest conditions (e.g., recent weather and date harvested). High moisture poses potential issues with storage and immediate use for energy production. Cobs with 10% to 30% moisture content are ideal for energy production. Cob moisture content has been found to be a critical factor in long term storage. Smith et al. (1985) examined the outside storage of corn cobs in piles with varying initial moisture values of 28.0 to 38.5%. The findings of this study suggested that ventilation with ambient air is needed for reducing cob spoilage/deterioration. Ventilation allowed for quicker reduction of interior moisture and, in turn, reduced the cob dry matter loss through microbial decomposition. Mold growth, evidence of cob deterioration, was present in all smaller scale piles except the ventilated pile. The importance of ventilation in corn cob storage was confirmed in an earlier study by Dunning et al. (1948). Spontaneous combustion, which may result in fire hazards, is also a concern when dealing with large piles of high moisture material. However, although these studies showed that ventilation improved cob storage, further research is needed to determine if the reduction in cob spoilage offsets the cost of electricity and equipment needed for pile ventilation.

Corn cob use as an energy feedstock requires large amounts of storage area. At the farm-gate level, this requires the farmer to allocate a portion of his land area to storage prior to collection by aggregators. It was determined that storage area is highly dependent on the piling method (Smith et al. 1985). A single circular pile would optimize the mass stored per unit area.

However, restrictions due to available equipment, stacking methods and ventilation may require alternative pile configurations, and increase the necessary storage area.

Another important issue associated with cob collection relates to the fact that it slows down grain harvest. Based on the acreage and available equipment/manpower, additional time is needed to get the grain crop as well as the cob biomass out of the field. The time issue is in terms of crop quality, timeliness and the approach of winter conditions that effectively shut down harvest operations. However, new technologies are being developed to optimize the system so as to reduce this negative impact.

3.4 Competing Uses of Corn Cobs

A summary of the current uses of corn cobs in Ontario is presented in Table 2.4. Examples include use in paper, particle board, chemicals and mushroom propagation. It must, however, be noted that such competing uses are on a very small scale in Ontario.

3.5 County Level Estimates of Corn Cob Biomass Availability in Ontario

Estimates of corn cob production were based on 2004-2008 corn grain production. The study assumes a cob to corn grain ratio of 0.16 at 15.5% moisture level, expressed in kg/ha basis. Thus, using Chatham-Kent as an example:

Estimated Annual Cob Yield [Dry Weight] = average grain yield (kg/ha)*0.16
= 8,574*0.16
= 1,371.8 kg/ha/yr

The product of average cob yield and land area under corn production in a county provides an estimate of the yearly gross amount of cobs per county. Thus, in Chatham Kent, where average land area under corn is 51,394.5 ha:

Estimated Gross Annual Cob Yield [Dry Weight] = 1,371.8 kg/ha/yr*51,394.5 ha
= 70,503.0 t/yr

As shown in Table 3.1 and Figure 3.1, assuming corn cobs are harvestable from all counties (except those in the Northern geographical region), a total of 834,523.0 tonnes of corn cobs could be sustainably removed as feedstock for the bioenergy industry, annually, assuming 100%

recovery during harvesting. Assuming a 90% recovery rate to account for harvesting inefficiency, the province could supply a total yield of 751,071 tonnes of dry corn cobs per year.

Table 3.1: Sustainably Removable Corn Cobs in Ontario by Region.

Region	Land Area (ha)	Average Cob Yield (kg/ha)	Total Potential Yield (Mg/yr)	% of Total Ontario Yield
Southern Ontario (10)	312,067	1,271	405,614	49
Western Ontario (10)	210,422	1,182	248,766	30
Central Ontario (8)	59,219	1,017	60,220	7
Eastern Ontario (8)	97,832	1,226	119,923	14
Total	679,540	1,174	834,523	100

In this analysis, we ignored the sustainability effect of cobs and therefore may be overestimating how much cob is sustainably removable under Ontario conditions. We did not factor in the contribution of cobs to sustainability because of the uncertainties of the role of cobs on SOM dynamics. There is virtually no report in the literature to provide any insight on the role of cobs in SOM dynamics, particularly SOM formation. Whereas some researchers speculate that cobs merely decompose slowly to release CO_2 into the atmosphere (Greer, 2008; Hanway, 2003), others assume that since the decomposition process is critical for fuelling soil biology (the soil 'food web'), the microbial biomass resulting from the process adds to SOM formation (Voroney, personal communication). Assuming all cobs (16% of stover) are removed from ‘qualified’ lands under CS and CSW rotations in the Elora scenario described earlier, total SRR based on land area distribution under the two rotation types would be reduced by 29% across Ontario (Kludze, unpublished data). Research in this area needs to be seriously considered to ensure sustainability in corn cob removal on a large scale.

3.6 Break-even Analysis of Corn Cobs

Similar to Section 2.6, the estimated break-even price of cobs was based on the replacement nutrient costs (Table 2.11), the harvest costs and farm-gate storage costs. Commercial fertilizers, the predominant method of soil amendment, have seen increased use and have been increasing in price, in general terms, in recent years. However, the low nutrient content of corn cobs means that low amounts of nutrients are removed with cobs at harvest. Although these nutrients still need to be replaced to maintain soil nutrient levels, the replacement costs are lower, compared to the removal of all of the stover. Despite the harvesting methods identified in Section 3.2, the use of dedicated machinery is likely the only feasible harvesting solution for corn cobs. The break-even price and harvesting costs of three corn cob harvesting scenarios are given in Table 3.2.

Table 3.2: Harvesting costs and break-even prices for three different corn cob harvesting methods.

Operation	Cost ($/t)		
	Cob Collection Device **50 ha Farm** 1,000 kg/ha	Cob Collection Device **100 ha Farm** 1,174 kg/ha	Cob Collection Device **200 ha Farm** 1,300 kg/ha
Machinery	112.98	48.12	21.73
Storage[a]	4.00	4.00	4.00
Total Harvesting Cost	116.98	52.12	25.73
Total Nutrient Cost @ 2008 Prices	23.72	23.72	23.72
Total Nutrient Cost @ 2010 Prices	17.77	17.77	17.77
Break-Even Price @ 2008 Prices	140.70	75.84	49.44
Break-Even Price @ 2010 Prices	134.75	69.88	43.49

[a]Stewart and McDonald 2008

The Vermeer CCX770 cob harvester costs approximately $53,665 US (Farm Industry News 2010). This cob harvester is pulled behind the combine and it separates cobs into a dedicated storage bin. The Super M-series Corn Stalk Special also bales corn stalks and leaves them behind on the field. This calculation assumes a 10 year repayment period. Given the cob yields identified in Table 3.1 as a guide and somewhat average Ontario farm sizes (50-200 ha), the harvesting costs of corn cobs appear to be heavily dependent on farm size. In general, the results are in a similar range to those in Table 2.13. Larger farms with higher yields seem to have reasonable costs, whereas corn cob harvesting seems prohibitive for smaller, less productive farms. Additional costs not present in the analysis include increased harvesting times, and machinery maintenance and storage costs. Corn cob storage prices may also be underestimated due to the fact that they do not ‘bale’, like the other crop residues; in addition, considerable cost and management may have to be allocated to cob storage.

3.7 Conclusions and Recommendations

Corn cobs represent a small component of corn residues, but provide an environmentally sustainable and economic alternative feedstock for the bioenergy industry. Assuming we were using the Elora (ERS) scenario, the total annual removable residue from the rotation scenarios would be about 1.1 million tDM, while the removable cob estimate would be 0.83 million tDM sustainably removable crop residue. This analysis indicates that there are several reasons for promoting the use of corn cobs as a feedstock for the biofuel industry in Ontario: 1) cobs are abundant in the Ontario and can be harvested in all corn growing counties in Ontario; 2) cobs have insignificant amounts of nutrients and the reduced cost of nutrient replacement for cob collection allows for greater profit potential in feedstock collection; 3) cobs constitute only about 16% of corn stover; and 4) cobs have low sulfur and ash content, and have good heating value, thus making them relatively more suitable as a feedstock for generating heat and electricity. However, very little is known about the actual impact of cob removal on essential soil ecosystem services, such as soil erosion, soil carbon, or nutrient (especially micronutrient) cycling. More research is needed to assess these impacts and to identify the cheapest and safest methods required for farm-gate level corn cob storage.

SECTION 4.0: ESTIMATED BIOMASS AVAILABILITY FROM DEDICATED BIOMASS CROPS

4.1 Estimated Biomass Availability from Dedicated Energy Crops

There has been growing interest in using perennial grasses as a renewable feedstock for generating electricity, biofuels and other industrial uses because of their potential to reduce greenhouse gas (GHG) emissions relative to fossil fuels, and to serve as carbon sinks by sequestering carbon in the soil (McLaughlin and Walsh 1998). Research programs are evaluating a variety of potential bio-energy crop species, such as Miscanthus *(Miscanthus spps.)*, switchgrass (*Panicum virgatum)*, big blue stem (*Andropogon gerardii)*, prairie cord grass (*Spartina pectinata*), common reed (*Phragmites australis*), hybrid corn (*Zea mays*) and hybrid sorghum (*Sorghum bicolor* (L.) *Moench*). There are breeding programs underway to develop higher yielding varieties of these species, and agronomic research is investigating the establishment, weed control, fertility, harvest timing (fall versus spring) and handling systems, along with the environmental attributes of these crops.

Switchgrass and Miscanthus have been identified as among the best choices for low input biomass production and are the focus of this study. Although these two biomass crops have been studied extensively in Europe (Lewandowski 2003; DEFRA 2001), very limited work has occurred in Ontario. In recent years, field and laboratory research related to agronomic and quality issues of the crops have begun at the University of Guelph, and there is ongoing biomass crop research at several research stations across Ontario.

To be favourably considered as a viable bio-based energy system, biomass crops must compete successfully as both crops and fuels (Khanna et al. 2008). Farmers will only convert their land into production of biomass crops when these crops provide an economic return that is at least equivalent to the returns from the most profitable conventional cropping alternatives. This study evaluates the farm-gate level availability, and the costs of production and procurement process for switchgrass and Miscanthus. The two major objectives of this portion of the study are to estimate how much of the two biomass crops can be potentially produced in Ontario, given the land base of the province, and to estimate the break-even prices of switchgrass and Miscanthus, in terms of production costs, under Ontario conditions.

4.2 Potential Land Base for Producing Energy Crops

We first examined the land base of Ontario to determine the capability of lands for growing switchgrass and Miscanthus. In the context of this study, land capability refers to lands meeting the minimum requirements for growing the two dedicated biomass crops, based on agricultural capability rating, as defined by the Canada Land Inventory (CLI). In this classification, lands are grouped into seven classes on the basis of soil and climate characteristics, according to their potentials and limitations for agricultural use. Table 4.1 provides definitions and descriptions of these land classes.

Table 4.1: Definition and description of Land capability classes for mineral soils in Ontario

CLASS 1	LAND IN THIS CLASS EITHER HAS NO OR ONLY VERY SLIGHT LIMITATIONS THAT RESTRICT ITS USE FOR THE PRODUCTION OF COMMON AGRICULTURAL CROPS**.**
Land in Class 1 is level or nearly level. The soils are deep, well to imperfectly drained under natural conditions, or have good artificial water table control, and hold moisture well. They can be managed and cropped without difficulty. Productivity is easily maintained for a wide range of field crops.	
CLASS 2	LAND IN THIS CLASS HAS MINOR LIMITATIONS THAT REQUIRE GOOD ONGOING MANAGEMENT PRACTISES OR SLIGHTLY RESTRICT THE RANGE OF CROPS, OR BOTH.
Land in class 2 has limitations which constitute a continuous minor management problem or may cause lower crop yields compared to Class 1 land but which does not pose a threat of crop loss under good management. The soils in Class 2 are deep, hold moisture well and can be managed and cropped with little difficulty.	
CLASS 3	LAND IN THIS CLASS HAS LIMITATIONS THAT REQUIRE MODERATELY INTENSIVE MANAGEMENT PRACTISES OR MODERATELY RESTRICT THE RANGE OF CROPS, OR BOTH**.**
The limitations are more severe than for Class 2 land and management practices are more difficult to apply and maintain. The limitations may restrict the choice of suitable crops or affect one or more of the following practices: timing and ease of tillage, planting and harvesting, and methods of soil conservation.	
CLASS 4	LAND IN THIS CLASS HAS LIMITATIONS THAT REQUIRE SPECIAL MANAGEMENT PRACTISES OR SEVERELY RESTRICT THE RANGE OF CROPS, OR BOTH.
Land in Class 4 has limitations which make it suitable for only a few crops, or the yield for a wide range of crops is low, or the risk of crop failure is high, or soil conditions are such that special development and management practices are required. The limitations may seriously affect one or more of the following practices: timing and ease of tillage, planting and harvesting, and methods of soil conservation.	
CLASS 5	LAND IN THIS CLASS HAS LIMITATIONS THAT RESTRICT ITS CAPABILITY TO PRODUCING PERENNIAL FORAGE CROPS OR OTHER SPECIALLY ADAPTED CROPS.
Land in Class 5 is generally limited to the production of perennial crops or other specially adapted crops. Productivity of these suited crops may be high. Class 5 lands can be cultivated and some may be used for cultivated field crops provided unusually intensive management is employed and/or the crop is particularly adapted to the conditions peculiar to these lands. Cultivated field crops may be grown on some Class 5 land where adverse climate is the main limitation, but crop failure can be expected under average conditions. Note that in areas which are climatically suitable for growing tree fruits and grapes the limitations of stoniness and/or topography on some Class 5 lands are not significant limitations to these crops.	
CLASS 6	**LAND IN THIS CLASS IS NONARABLE BUT IS CAPABLE OF PRODUCING NATIVE AND OR UNCULTIVATED PERENNIAL FORAGE CROPS**.
Land in Class 6 provides sustained natural grazing for domestic livestock and is not arable in its present condition. Land is placed in this class because of severe climate, or the terrain is unsuitable for cultivation or use of farm machinery, or the soils do not respond to intensive improvement practices. Some unimproved Class 6 lands can be improved by draining and/or diking.	
CLASS 7	**LAND IN THIS CLASS HAS NO CAPAPBILITY FOR ARABLE OR SUSTAINED NATURAL GRAZING.**
All classified areas not included in Classes 1 to 6 inclusive are placed in this class. Class 7 lands may have limitations equivalent to Class 6 land but they do not provide natural sustained grazing by domestic livestock due to climate and resulting unsuitable natural vegetation. Also included are rockland, other nonsoil areas, and small water-bodies not shown on maps. Some unimproved Class 7 land can be improved by draining or diking.	

Source: http://geogratis.cgdi.gc.ca/CLI/index_agriculture.html

Soils within a capability class are similar with respect to the degree, but not necessarily to the kind, of agricultural limitation. Each class includes many different kinds of soil. In summary, Class 1 to 4 lands are considered capable of sustained production of common field crops, such as corn, soybean, and wheat (Table 4.1). The need for management practices increases, and/or the possible range of crops decreases, from Class 1 to Class 4, and Class 5 lands are capable of use only for producing perennial forage crops, or specially adapted crops. Class 6 lands are capable of providing only sustained natural grazing for domestic livestock, while Class 7 lands are incapable of use for either arable culture or grazing. Overcoming any particular limitation would be influenced by the financial implications of such a decision. Thus, even lands with very severe limitations may be modified to enable biomass crop production, given the right economic conditions. For example, more production input (e.g., irrigation or drainage) may need to be allocated to the more marginal lands (Classes 4-5) to be able to attain a similar level of productivity, as compared to the high-valued lands (Classes 1-3). Since the financial costs involved in such a remedial venture may be economically unfeasible, particularly for Classes 6 and 7 lands, the analysis in this study was limited to Classes 1 to 5 lands.

Potential biomass productivity in each county of Ontario was determined by land area and other factors affecting land availability, such as environmental constraints, and governmental energy and agricultural policies. The land-base available for growing biomass crops will be, henceforth, referred to as ‘tillable land’. The following five criteria were applied to the OMAFRA land database to separate land capable of growing biomass energy crops from non-capable land:

1. The land is not crown land (which is mainly forest/rangeland);
2. The land is currently used for, or can easily be converted to, agriculture (i.e., Classes 1 to 5 lands);
3. The land is not permanent wetland, swamp, marsh, bog, or open water (e.g., lakes) (excluded from the analysis because of environmental regulations and constraints in the use of such lands);
4. The land is not forested land (excluded because the conversion of forests to biomass crops represents a decrease in terrestrial carbon storage, which is undesirable from the standpoint of GHG emissions); and

5. The land excludes dedicated *non-agricultural* uses, such as residential, commercial, industrial, institutional, wilderness, wildlife, recreation, research and experimental plots, and roads.

Thus, tillable land is defined by total land area minus built-up areas, lands for non-agricultural uses, woodlands/forests, large lakes and permanent wetlands, swamps, marsh and bog. The Canada Land Inventory (CLI) database contains tillable land area under each of the seven land capability classes on a geo-township basis. To obtain tillable land on a county basis, all geo-township data in each county was pooled. As an example, the available tillable land area for the Municipality of Chatham-Kent is summarized in Table 4.2.

Table 4.2. Available tillable land for growing energy crops in Chatham-Kent Municipality

Land Capability Class	Total Land Area by Class (ha)	Tillable Land Area by Class (ha)	Tillable land area as % of Total Land area (%)
1	25,178	20,591	82
2	169,370	144,267	85
3	38,880	28,332	73
4	296	249	84
5	703	327	46
ALL	234,427	193,766	83

To provide estimates of biomass availability on a county basis, it was assumed there was no restriction on the conversion of any land class to energy crop production, and that the proportions of land classes that would be allocated to production would be dictated by economic considerations. The amount of a dedicated crop biomass that can be potentially produced from each land class in a county was obtained by multiplying the tillable land area in a county by its corresponding average productivity (yield/ha). Table 4.3 provides the names of the counties, administrative divisions, or municipalities within each region we considered in this study. Figures 4.1 to 4.4 map land capability Classes 1-6. Ottawa in the Eastern region, Muskoka, Parry Sound and Haliburton in Central Ontario, as well as all of the counties in the Northern region were excluded from this analysis because either there were no data available, or the data provided were found to be unreliable. For example, in the case of Muskoka, Parry Sound and Haliburton, the tillable land area for some capability land classes was found to be more than the total land area in these counties. According to staff in the OMAFRA GID Section, data for Ottawa County have been completely removed from the public domain because of some unresolved problems.

Table 4.3. Composition of selected regions within Ontario

Region	County/Division/Municipality
Southern Ontario (10 Counties)	1. Brant 2. Chatham-Kent 3. Elgin 4. Essex 5. Haldimand-Norfolk 6. Hamilton 7. Lambton 8. Middlesex 9. Niagara 10. Oxford
Western Ontario (10 Counties)	1. Bruce 2. Dufferin 3. Grey 4. Halton 5. Huron 6. Peel 7. Perth 8. Simcoe 9. Waterloo 10. Wellington
Central Ontario (7 Counties)	1. Durham 2. Hastings 3. Kawartha 4. Northumberland 5. Peterborough 6. Prince Edward 7. York
Eastern Ontario (7 Counties)	1. Frontenac 2. Lanark 3. Leeds & Grenville 4. Lennox & Addington 5. Prescott & Russell 6. Renfrew 7. Stormont, Dundas & Glengarry

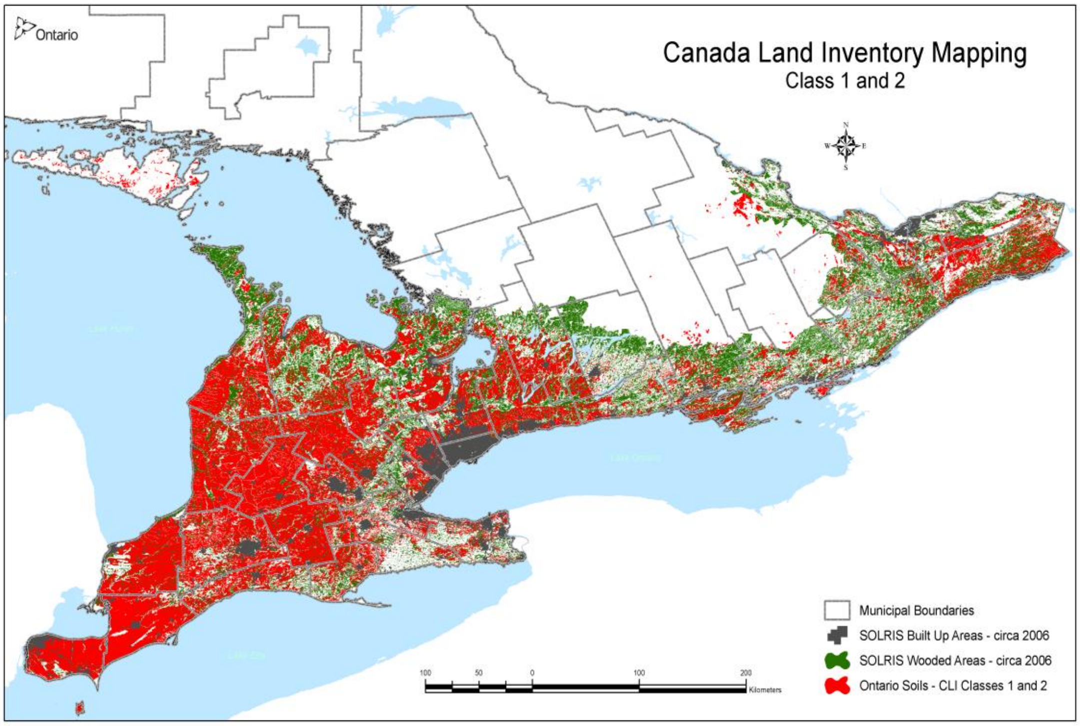


Figure 4.1: Map of Class 1 and 2 Soils in Ontario (OMAFRA, 2009)

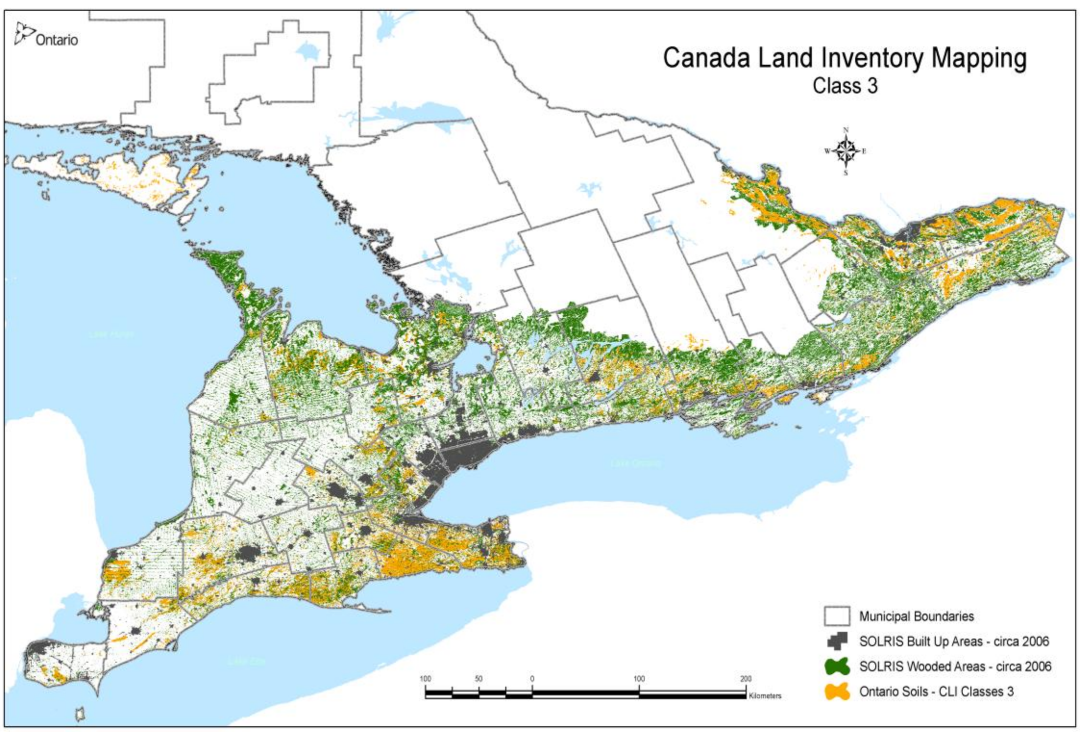


Figure 4.2: Map of Class 3 Soils in Ontario (OMAFRA, 2009)

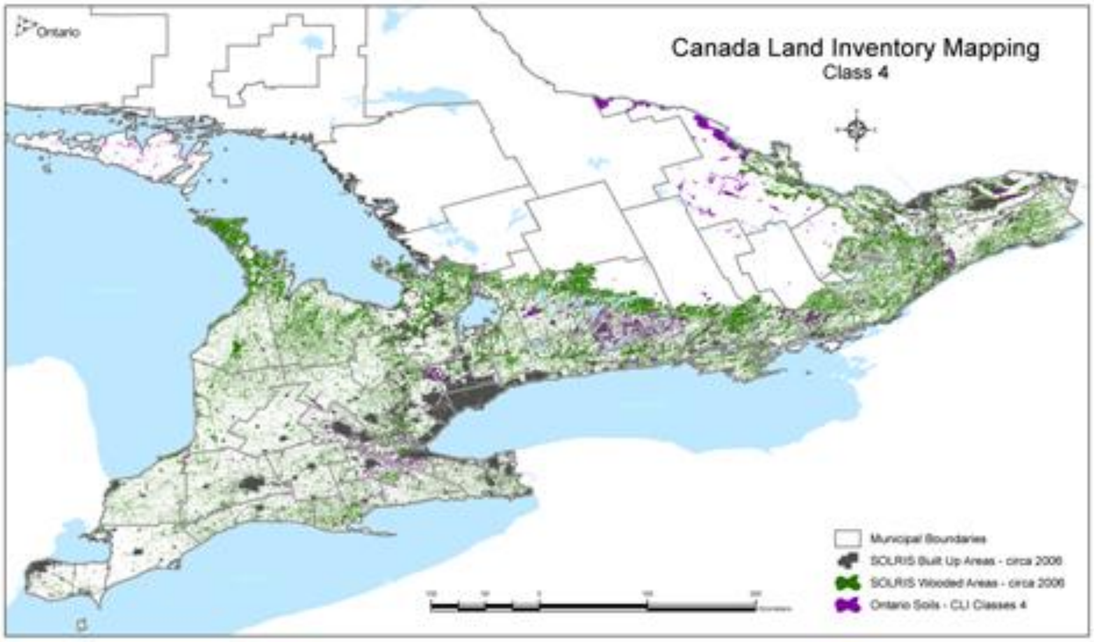


Figure 4.3: Map of Class 4 Soils in Ontario (OMAFRA, 2009)

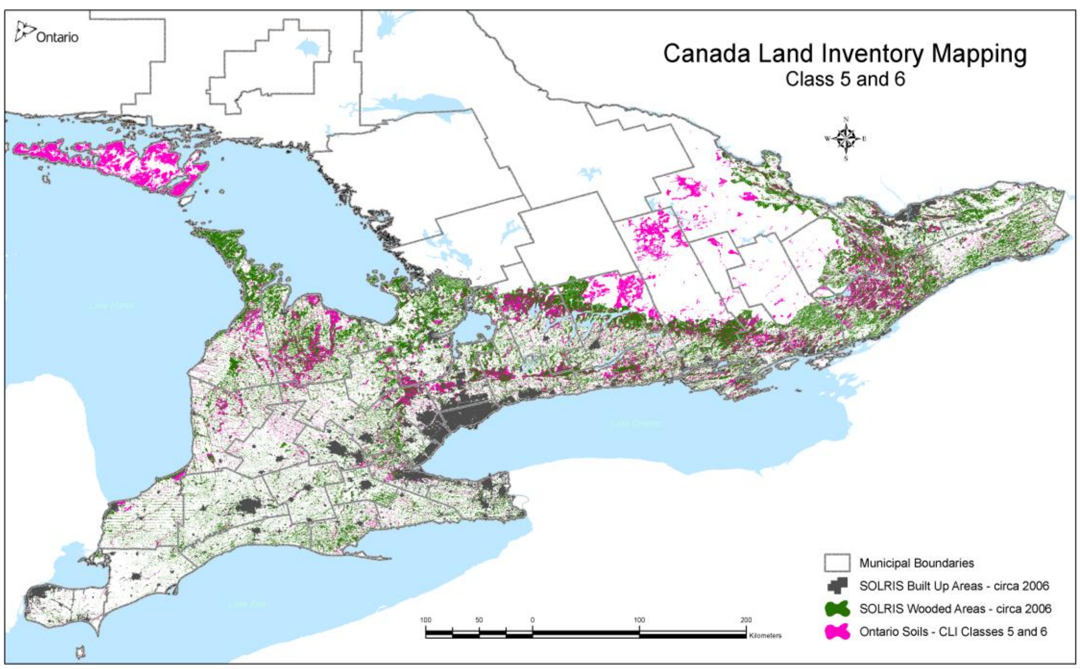


Figure 4.4: Map of Class 5 and 6 Soils in Ontario (OMAFRA, 2009)

Biomass productivity on higher capability lands was assumed to be higher. Although a recent paper by Wullscheleger et al. (2010) found no significant statistical correlation between productivity and land capability class, for either lowland or upland ecotypes of switchgrass, in an aggregate study of the US, it is likely that there is still some degree of yield response in more spatially explicit situations. There is undoubtedly a demand for sources of biomass. For example, OPG has suggested an annual 2 million tDM biomass requirement for its predicted operations and apart from OPG, there are other potential markets for biomass as well. However, the OPG requirement provides a likely estimate of the minimum demand for biomass. In order to estimate potential biomass production, scenarios involving the conversion of 5%, 10%, 25%, 60% and 100% of tillable lands in a county were considered. Results of these scenarios are discussed under the individual biomass crops in Sections 4.1 and 4.2.

Some of the important biomass properties and characteristics of switchgrass and Miscanthus are summarized in Table 4.4.

Table 4.4: Relevant properties and biomass characteristics of Switchgrass and Miscanthus.

Characteristics	Switchgrass (Panicum Virgatum)	Miscanthus (*Miscanthus* ssp.)
Photosynthetic pathway	C4[a]	C4[a]
Day length	Short day plant[a]	Long day plant[a]
Soils	Wide range[a]	Wide range[a]
Optimum Soil pH	4.9-7.6[b]	NA
Water supply	Drought tolerant; moderately tolerant of flooding, but does not grow well in wet areas[b g]	Not tolerant to stagnant water and prolonged drought periods; no soil compaction[b, g]
Moisture content at harvest	15[b]	15 [a]; 16-62 [d]
Ash (% of DM)	4.5-5.8 [c]	1.6-4.0 [c]
N (% of DM)	0.71-1.37[c]	0.19-0.67
K (% of DM)	0.21-0.36 [a ,f]	0.31-1.28 [a ,f]
Ca (% of DM)	0.28-0.73 [c]	0.08-0.14 [c]
Cl (% of DM)	0.03 to 0.5 [c]	0.10-0.56[c,f]
S (% of DM)	0.12 [c]	0.04-0.19 [c]
Si (% of DM)	NA	NA
Holocellulose (cellulose+hemicellulose)	54-67[h;i]	64-71[a]
Gross Heating value (dry MJ kg^{-1})	17.0 [d]	17.1 [d]
Net energy content (dry MJ kg^{-1})	NA	15.8-16.5[a]
Ash fusion (melting) temperature (C)	1016[h]	1090[a]

[a]McLaughlin et al. 1996
[b]Christian et al. 1997
[c]Sladden et al. 1991
[d]Vogel 1996
[e]Ma et al. 1999
[f]Lewandowski 2000
[g]Moser and Vogel 1995
[h]Acaroglu and Aksoy 1998
[i]Moilanen et al. 1996

On average, the characteristics of Miscanthus are similar to those of switchgrass. However, switchgrass has a higher ash content, which can be reduced if harvesting is done in the spring (overwintering following a fall swathing), after the plants lose their leaves. Biomass contains inorganic elements which are released from the ash during combustion and deposited on the surfaces of the combustion unit, 'fouling' it. Slagging relates to the melting of these deposits, forming a glassy layer. Interaction of the deposits with the metal surfaces can accelerate corrosion, which gradually destroys the metal surface, leading to increased maintenance requirements, reduced service life of the installation, and reduced efficiency of the combustion unit leading to higher operating costs. The formation of deposits is closely related to corrosion. This means that a decrease in deposit formation will also reduce corrosion problems. The concentration of both K and Cl is a major factor in deposit formation. The concentration of K and Cl in switchgrass is similar to that in Miscanthus (Table 4.4). In general, moderate corrosion problems for both switchgrass and Miscanthus have been reported (Elbersen et al., 2010)

SECTION 4.1: BIOMASS AVAILABILITY FROM SWITCHGRASS

4.1.1 Brief Description of Switchgrass (*Panicum virgatum)*

Among the many agricultural crops evaluated as potential biofuels, switchgrass has been identified as a promising feedstock for conversion (Sanderson et al. 1996; McLaughlin et al. 2002; Parrish and Fike 2005). Switchgrass is a perennial warm-season herbaceous crop that, historically, has been an important component of the North American tallgrass prairie. Ranging from northern Mexico to southern Canada and from the Atlantic coast to the Rocky Mountains, switchgrass has broad adaptability, high growth rates, and tolerates a wide variety of climatic and soil conditions (Wullscheleger et al. 2010). Switchgrass can adapt to marginal lands, and tolerates soil water deficits and low soil nutrient concentrations (Sokhansanj et al. 2009). Two distinct forms, or ecotypes, are observed across its geographic range: a lowland type found in wetter and more southern habitats of the US; and an upland type found in drier mid and northern latitudes (Porter 1966; Sanderson et al. 1996; Casler et al. 2004). A variety of lowland and upland cultivars are available and cultivars of both ecotypes are being considered as a feedstock for biofuels and other industrial end-uses. Therefore, cultivar selection, crop management decisions and expectations regarding biomass yield will depend to a great extent on geographic location (Parrish and Fike 2005).

Working with Resource Efficient Agricultural Production (REAP) – Canada, Samson (2007) compiled a very informative 'Management Guide' on switchgrass production in Ontario. Most of the information provided in this report was taken from that Management Guide. In Canada, switchgrass has been under investigation as a bioenergy crop since 1991. Several market opportunities involving switchgrass are now emerging for growers in Eastern Canada. For example, switchgrass is seriously being considered as an herbaceous energy crop for ethanol and electricity production, and as a feedstock for paper pulp production. In Ontario, switchgrass produces most of its biomass in the warm summer months of June through August. The successful production of the grass requires different production techniques and harvest schedules than those used for cool-season forage grasses, such as timothy and bromegrass. In particular, switchgrass can be relatively slow to establish. As stated, switchgrass varieties are classified into two broad categories: lowland varieties developed under floodplain conditions; and upland ecotypes developed under drier upland sites. Research indicates that lowland varieties are more susceptible to winterkill (Samson 2007), while upland varieties in most areas of Ontario will provide farmers with the best productivity and stand longevity. However, in Southwestern Ontario, some northern lowland ecotypes may prove to be adequately hardy. ‘Cave-in-Rock’ is the most widely planted variety in the Northeastern United States and this variety is gaining popularity in Ontario. Early maturing varieties, such as ‘Forestburg’, ‘Sunburst’, and ‘Shelter’, are being considered for their winter hardiness and productivity in more northerly areas of Ontario. Current research recommends that Ontario farmers choose varieties originating from the eastern United States, as these tend to be more disease resistant. Some western originating switchgrass varieties have developed leaf diseases in the province. Other switchgrass varieties, including ‘Carthage’ and ‘Niagara’, are currently being tested for their agronomic characteristics, such as planting dates, establishment, adaptability, seedling vigour, disease resistance, winter hardiness and yield, at different locations across Ontario. Once fully established in Ontario, switchgrass can typically produce 8-12 t/ha of harvestable dry matter by the fall season (Samson 2007). Although overwintering harvest at spring time will cause some reduction in harvestable yields, the resulting material will have improved quality for combustion applications. Research is ongoing to optimize the yield and quality of switchgrass through both variety improvement and harvest management.

4.1.2 Current Switchgrass Production Requirements and Methods in North America

Establishment Years

Switchgrass seeds are usually sold based on their pure live seed (PLS) per hectare, as the seed varies greatly in purity and germination. Eight to 10 kg PLS/ha are recommended for a successful establishment. Seed lots with equal amounts of PLS may differ in their volume of bulk seed. Newly harvested switchgrass seed can have high seed dormancy and high dormancy seedlots require higher seeding rates for successful field establishment. For newly harvested seeds, a dormancy rating of 10 percent or less is considered excellent. Experience in Ontario indicates that switchgrass is easier and faster to establish on well-drained loam and sandy soils than on clay soils (Samson 2007). The roots and crowns of switchgrass spread more readily on these lighter soil types. This results in a maximum yield level being achieved in a shorter time period. Typically, switchgrass produces about 30% of its biomass potential in the first year, 70% in the second year and 100% of maximum biomass production by the third year. Switchgrass seed is fairly small and, therefore, poor contact with the seedbed, caused by clay clumps, will result in poor or uneven germination (Samson 2007). Ensuring good contact between seeds and soil after planting is, therefore, highly recommended on all soil types, especially on clay soils. As switchgrass is fairly slow to form a canopy, weed control is critical to achieving a successful establishment. In the fall preceding establishment, fields should be sprayed with a broad-spectrum herbicide to eliminate problem perennial weeds, such as quackgrass, from invading the establishing stand (Samson 2007). Chemical weed control can be used in the fall prior to establishment, pre-plant and post-plant, although no herbicides are presently registered for this use in Ontario. It has been recommended that hormone herbicides such as 2,4-D be avoided as they are known to reduce development of switchgrass when applied early in the establishing year (Parrish et al. 2008). Switchgrass stands that are initially weedy often become well established with appropriate management in subsequent years, although the stands tend to be uneven (Parrish et al. 2008)

Due to its extensive perennial root system and drought tolerance, switchgrass is relatively productive on medium to lower fertility soils, compared to most annual field crops. Switchgrass is well suited to be grown in areas with less than 2600 crop heat units (CHU), which are marginal for corn and soybean production. Soil pH should be above 6.0 for optimal yields. Soil preparation should include one or two passes with a harrow (or disk) and the seedbed should be packed. In conventionally tilled fields, seeding is best performed with a Brillion type seeder at a seeding depth of 0.5-1.0 cm. In the spring, seeding should be performed when soils are relatively warm, usually between May 15th and June 10th.

No-till soybean seed drills are commonly used for no-till seeding of switchgrass. A stand is successfully established if 10-32 seedlings per m^2 can be found at the end of the establishment year. Spring cultivations at 7-10 day intervals prior to seeding can help reduce annual weed pressure in fields. Grass weeds, such as barnyard grass, foxtail and crab grass, are the most difficult to control in switchgrass stands. It is difficult to find herbicides that effectively remove grass weeds from switchgrass seedlings without causing injury to the switchgrass. Research is ongoing on this issue, but loss of stands or delayed establishment due to weed competition is more likely to occur with seedings on heavier soils (Samson 2007).

While nitrogen fertilizer is normally applied annually to improve yields, nitrogen fertilization does not have to be utilized in the switchgrass establishment year for two major reasons: (1) switchgrass is an excellent nutrient scavenger in establishing fields; and (2) applying nitrogen (N) fertilizer commonly stimulates weed growth and this reduces the competitive ability of switchgrass. According to the OMAFRA guidelines for forage crops, potassium (K) and phosphorus (P) fertilizers are also not applied during establishment, unless levels are low (< 81 ppm for K and less than <10 ppm for P). Switchgrass seldom responds to K and P fertilizer as it has a large root system and relies on mycorrhizae for P uptake (Samson 2007). It is best to avoid manuring fields before planting to minimize weed competition. To ensure good winter hardiness and vigorous regrowth, it is recommended that switchgrass grown in the establishment year be overwintered prior to harvest (i.e., no harvest in the first year).

Production Years

Research conducted in eastern Canada indicates that maximum production is first attained during the third growing season (Samson 2007). Once established and properly maintained, a switchgrass stand will remain productive for an indefinite period. Experience in Ontario has shown that, if switchgrass stands are subject to winter injury or heaving, they can commonly recover in the subsequent growing season. Switchgrass has large underground carbohydrate reserves which help regenerate regrowth; therefore, even if subjected to winter injury, the plant is able to recover in the subsequent growing season.

Production Years: Fertilization & Weed Management

In most cases, the only operation required following harvesting is the application of N fertilizer. For a late fall or spring harvest regime, 50-60 kg of actual N per hectare per year is sufficient to sustain production. Research reports indicate that over-fertilization with N usually results in crop lodging, which ultimately results in yield reduction and harvesting difficulties (Samson 2007). By adopting a late winter or spring harvesting regime, P and K fertilization requirements are minimized. Usually no P or K is applied on medium to rich soils under switchgrass cultivation. It is recommended that soil concentrations of these two nutrients are monitored 2-3 years after establishment and fertilization performed if deemed necessary. Modest rates of solid and liquid manure and sewage sludge may be applied to established switchgrass stands when actively re-growing (typically in early June). Mowing and the use of properly labelled herbicides are recommended for weed control (Lawrence et al. 2006).

Production Years: Harvesting & Yields

As a biomass crop, switchgrass is best grown as a one-cut per year crop, with the harvest performed any time after fall dormancy (i.e., leaf yellowing) is well initiated. This ensures adequate nutrient and carbohydrate translocation to the root reserves to help encourage winter survival and prevents reduction in root shoot carbohydrate mobilization associated with new vegetative growth. This also improves biomass quality (with respect to undesirable nutrients such as K and Cl). Switchgrass can be harvested with the same field equipment used for hay production. The harvest period can include late fall, mid winter (in snow-free conditions) and early spring (anytime between mid-April and late-May). If fall cutting switchgrass, it is recommended to leave at least 10 cm of stubble to improve winter survival and reduce winter heaving. Early maturing varieties can be chosen to help create an earlier fall dry-down of the crop. As well, varieties that have minimal lodging and thin stems tend to dry down more effectively. Another common problem on heavier soils is that field conditions are too wet in the fall to enable baling and transport equipment for fall harvesting.

Delaying the harvest of switchgrass to the spring has the advantages of: (1) improving winter survival and weed control; (2) reducing nutrient extraction, resulting in reduced fertilizer requirements; (3) improving the combustion properties of the material; (4) reducing the ash content of switchgrass, typically from 5% in the fall to 3% in spring; and (5) reducing the moisture content at harvest to about 12-14%. This reduction in moisture content can eliminate the need for drying the harvested biomass prior to densification. Well-drained sandy soils offer the greatest flexibility for farmers in accessing fields under wet weather conditions. Similar to crop residues, harvest rates for perennial dedicated crops will need to be tailored to maintain sufficient cover for erosion control, and the time of harvest will need to be optimized for stand maintenance and wildlife protection (Johnson et al. 2010).

Preliminary studies on yields in Ontario indicate that, once fully established, switchgrass can produce 8-12 tDM per hectare per year (Samson 2007). Data on potential yields of switchgrass at specific agro-ecological regions within the province are lacking, although research in this area has been stepped up in recent years. In a recently published paper by Wullschleger et al. (2010), the authors reported no statistically significant response of switchgrass to variations in soil quality, but found a broad optimal temperature range for biomass yield. The latter authors identified ecotype, temperature, precipitation, and N fertilization as the most important predictors of switchgrass yield. Therefore, it is likely that yields will vary across Ontario depending on the magnitude of these variables in the various agro-ecological regions of the province.

4.1.3 Constraints and Limitations in Switchgrass Production and Procurement

Finding Suitable Varieties/Cultivars (for Winter Survival)

One of the major challenges in switchgrass production is the ability of the plant to survive the winter, especially during the establishment years. Winter survival is mainly determined by the length of the growing season of switchgrass. If a variety fails to mature sufficiently when winter sets in, severe winter damage to the stand can occur (Elbersen 2003). Lowland varieties are more susceptible to winterkill; however, in Southwestern Ontario, some northern lowland ecotypes may prove to be adequately hardy and included in mixed warm-season grass seedings in the future (Samson 2007). 'Cave-in-Rock' is the most widely planted variety for Northeastern USA. Winter survival, which indicates full establishment of over 50% for populations of switchgrass, requires a mean shoot stage (MSS) of about four to six collared leaves and a mean root stage (MRS) of four to six adventitious roots at the end of the growing season of the seeding year (O'Brien et al. 2008). O'Brien et al. (2008) concluded that, in the field, using an above ground metric, such as the MSS, provides a reliable predictor of seedling winter survival.

Weed Competition

Weed competition is a major problem in switchgrass establishment (O'Brien et al. 2008). Grass species, including barnyard grass, foxtail and crab grass, are the most difficult to control in switchgrass stands in Ontario (Samson 2007). It is difficult to find herbicides that effectively remove grass weeds from switchgrass seedlings without causing injury to the switchgrass. Weed control research has mainly been conducted on upland ecotypes of switchgrass. Research is ongoing on this issue and loss of stands or delayed establishment due to weed competition is more likely to occur with seedings on heavier soils. Currently, no herbicides are registered for use on switchgrass in Canada, but studies on weed control for switchgrass have shown that the herbicide atrazine often improves switchgrass establishment (Cassida et al. 2000). Guidelines from the United States are to use Aatrex atrazine at 1.1-2.2 kg/ha of active ingredient at, or soon after, planting. However, atrazine rates for Miscanthus are not yet registered in Canada and therefore the above rate may not apply for Ontario conditions. Basagran (bentazon) and Laddock (blend of atrazine and bentazon) are effective against most post-emergent broadleaf weeds, with minimal crop damage. An alternative method to chemical weed control is mowing the field to a height of 102 to 127 mm whenever the weeds reach 152 to 254 mm tall (Samson 2007).

Harvest Losses

As stated earlier, delaying the harvest of switchgrass to the spring has many advantages. However, the main problems identified with overwintering switchgrass in fields include: (1) breakage of the seed heads and leaves by winter winds and ice storms, where 20-30% of the total dry matter can typically be lost in fields; and (2) cutting the material in the spring can lead to large harvest losses due to material shattering because of its dry and brittle state at harvest (Samson 2007). Swathing standing switchgrass (i.e., cutting and putting in windrows) in the spring can substantially reduce harvest losses compared to harvesting with a mower conditioner. Alternatively, direct cutting with a forage harvester equipped with a kemper type header may be employed. Another possible harvest option is to fall mow and spring harvest the material. This approach, found to be promising from preliminary field results, may reduce winter breakage, and promote more rapid soil warming and field drying in the spring.

Combustion Quality Issues

There are no major concerns regarding switchgrass biomass quality. Translocation of nutrients, such as N, P, and K, as well as carbohydrates to the crown and root system as plants approach senescence ensures lower ash content of biomass at the end of the season. The reduction in ash content may also be attributed to increasing proportions of stem relative to leaf mass later in the growing season due to leaf loss during the winter. Delaying the harvest until spring could also increase the opportunity to leach minerals from the crop (Bakker and Jenkins 2003; Burvall 1997). Adler et al. (2006) also found that delaying harvest to spring increased the energy content of biomass due to reduced moisture and ash content. A summary of essential quality issues related to biomass combustion can be found in Table 4.4 above.

Environmental/Sustainability Issues

In the Management Guide for switchgrass production in Ontario, Samson (2007) noted that switchgrass and other warm-season grasses could help Canada achieve major greenhouse gas (GHG) emission reduction targets. Overall, switchgrass pellets can reduce GHG emissions by about 90% when compared with using an equivalent amount of energy in the form of fossil fuels. Switchgrass can also reduce GHG emissions by increasing the carbon stored in landscapes through increased carbon storage in roots and soil organic matter. It has been reported that land conversion to switchgrass on Conservation Reserve Program (CRP) plantings in the United States has led to 40 t/ha of CO_2 being stored compared to conventional land use (Liebig et al. 2008). Assuming a harvested grain corn yield of 6.5 t/ha and a switchgrass yield of 10 tonne/ha, switchgrass produces 185 GJ/ha of energy versus 120 GJ/ha for grain corn. If the fossil energy inputs used for crop production are subtracted from energy output, the net energy gain per hectare is 73% higher for switchgrass than grain corn.

Switchgrass has a higher root density than annual crops such as corn (Johnson et al. 2007a); therefore, the inclusion of such a perennial specie into feedstock production systems can help stabilize soils, which reduces erosion, improve water quality, and improve wildlife habitat (Johnson et al. 2007b). Switchgrass is well-known among wildlife conservationists as good forage and habitat for game bird species, such as pheasants, quail, wild turkey, and song birds, with its plentiful small seeds and tall cover (Hipple 2002). Moreover, with the late fall harvest regime associated with switchgrass, additional riparian benefits can be achieved since the fields remain unmanaged throughout much of the growing season.

4.1.4 Competing uses of switchgrass biomass

Switchgrass can be used in a variety of agricultural and energy markets (Samson 2007; Girouard and Samson 2000). Currently, it is being used for livestock bedding, as part of a dry cow ration/feed, as a mushroom compost substrate, as a horticultural or roadside mulch and in straw bale house construction. The current major interest, in Ontario, however, is its use as a commercial fuel pellet for heating. On-farm applications can include greenhouse heating, heating of livestock buildings and corn drying. Switchgrass can also be used as a feedstock for biogas production. Preliminary combustion trials with switchgrass have been conducted in both residential pellet stoves and commercial boilers in the province (Samson 2007). Fall harvested switchgrass appears to have more difficulty in combustion applications, when it is used as the only fuel, because of higher ash content. Overwintered switchgrass appears to have fewer limitations for use in combustion systems designed for higher ash fuels. Experience has also shown that overwintered switchgrass has superior pellet durability when compared with fall harvested switchgrass. A low price and relatively good mechanical characteristics should make switchgrass an attractive fibre for filling and stiffening in thermoplastic composites. Switchgrass has been evaluated for paper pulp production and as a reinforcing fibre in polypropylene composites (Goel et al. 1998). The potential ethanol production yield when switchgrass is used as a feedstock was calculated to be 262 kg ethanol/tDM. This yield is comparable to the theoretical ethanol yield from woods like willow (Elbersen and Bakker 2003). Table 4.1.1 summarizes the competing uses of switchgrass and Miscanthus in North America.

Table 4.1.1. Competing uses of switchgrass and Miscanthus biomass feedstocks.

Current and Potential Future Competing Uses	**Biomass Type**	
	Switchgrass	***Miscanthus***
Feed for Livestock (e.g. Dairy Cattle)	X[1]	NA[2]
Bedding for Livestock	X	NA
Insulating/Building Materials	X	X
Medium for Mushroom Propagation	X	X
Particle Board	X	X
Direct Combustion/Gasification	X	X
Pellets/Briquettes for Large-scale Energy production	X	X
Paper	X	X
Industrial Uses/Biomaterials/Biochemicals (e.g. furfural)	X	X
Transportation Fuel (e.g. Cellulosic ethanol)	X	X

[1]X= Biomass used; [2]NA =information not available

4.1.5 County Level Assessment of Switchgrass Biomass Availability

Biomass productivity varies as a function of geographic location, climate, soils/land quality and crop management practices (Wullscheleger et al. 2010; Johnson et al. 2009). There is very limited information on field trials and productivity of biomass crops in Ontario. However, preliminary findings indicate that switchgrass can typically produce 8-12 t/ha of harvestable dry matter by the fall season, once fully established (Samson 2007). If harvesting is delayed until springtime (overwintering), some reduction in harvestable yields is likely, but the resulting material may have improved combustion quality. Research is ongoing to optimize the yield and quality of switchgrass through both variety improvement and harvest management.

Heaton et al. (2004) extracted data from several peer-reviewed publications and evaluated the productivity of switchgrass as a function of N fertilization, growing degree days, temperature and precipitation. Their analysis showed that yield responded positively to water and N, but not to temperature. Wullscheleger et al. (2010) found yield increases with increasing temperature up to a point, followed by decreases, under US conditions. The latter researchers did not observe any strong correlation between yield and precipitation across switchgrass ecotypes, although low precipitation during the growing season did appear to limit yield. In this study, spring harvesting and a productivity (yield/ha/yr) response of switchgrass to land class were assumed. Biomass productivity was assumed to be equal to 7 tDM/ha in the "high valued lands" (Classes 1, 2 and 3 lands), 6.3 tDM/ha in Class 4 land (i.e., 90% of the productivity of high valued lands) and 5.6 tDM/ha in Class 5 land (i.e., 80% of the productivity of high valued lands). These yield values may be conservative for the high valued lands and less conservative for the marginal lands. Based on these assumptions, the following five scenarios for tillable land use in producing switchgrass were created: (1) 5%; (2) 10%; (3) 25%; (4) 60%; and (5) 100% land use. Potential county-based biomass production results were aggregated into regional production estimates (individual county-based production is provided in Appendix B). Each scenario is aimed at meeting at least the annual 2M tDM biomass threshold, assuming 100% biomass recovery at harvest. The results of these scenarios are summarized in Table 4.1.2.

Table 4.1.2: Estimated amounts of switchgrass biomass by percentage of land class allocated to switchgrass production (tDM/yr)

Land Class	***Land Planted to Switchgrass***				
	5%	**10%**	**25%**	**60%**	**100%**
			Southern Ontario Region		
1	92,988	185,976	464,941	1,115,858	1,859,763
2	346,002	692,003	1,730,009	4,152,021	6,920,035
3	181,957	363,913	909,781	2,183,475	3,639,126
4	15,761	31,521	78,803	189,128	315,214
5	15,730	31,459	78,647	188,753	314,588
ALL	**652,436**	**1,304,872**	**3,262,181**	**7,829,235**	**13,048,726**
			Western Ontario Region		
1	319,049	638,098	1,595,244	3,828,585	6,380,976
2	283,950	567,900	1,419,749	3,407,398	5,678,997
3	134,192	268,384	670,959	1,610,301	2,683,835
4	113,038	226,076	565,190	1,356,456	2,260,760
5	44,473	88,945	222,363	533,672	889,454
ALL	**894,702**	**1,789,403**	**4,473,505**	**10,736,412**	**17,894,022**
			Central Ontario Region		
1	62,537	125,074	521,144	1,250,745	2,084,575
2	37,049	74,097	308,738	740,971	1,234,952
3	41,949	83,898	349,576	838,982	1,398,303
4	35,277	70,553	293,970	705,529	1,175,882
5	24,026	48,051	200,214	480,513	800,855
ALL	**200,837**	**401,673**	**1,673,642**	**4,016,740**	**6,694,567**
			Eastern Ontario Region		
1	10,720	21,439	53,597	128,633	214,388
2	125,951	251,902	629,754	1,511,410	2,519,017
3	116,012	232,023	580,059	1,392,141	2,320,235
4	77,527	155,054	387,634	930,322	1,550,537
5	29,278	58,556	146,390	351,336	585,561
ALL	**359,487**	**718,974**	**1,797,434**	**4,313,842**	**7,189,738**
			Ontario Total		
1	485,293.50	970,587	2,634,926	6,323,821	10,539,702
2	792,951	1,585,902	4,088,250	9,811,800	16,353,001
3	474,109	948,218	2,510,375	6,024,899	10,041,499
4	241,602	483,204	1,325,597	3,181,435	5,302,393
5	113,505.50	227,011	647,614	1,554,274	2,590,458
ALL	**2,107,461**	**4,214,922**	**11,206,762**	**26,896,229**	**44,827,053**

From Table 4.1.2, the largest potential biomass supply is obtainable in the Western and Southern Ontario regions. If all of the tillable land considered in this analysis (i.e., Classes 1-5 lands) were used, the combined production of these two areas would be over 30 million tDM switchgrass biomass. The use of only 25% land in either Western Ontario or Southern Ontario for producing switchgrass exceeds the target biomass of 2M tDM and the combined use of 10% land in the two regions would also meet the target. The use of either all of Class 2 lands or all of Class 3 lands in the two regions would also meet the 2M tDM biomass target. To meet this target value in Central or Eastern Ontario, more than 25% of all lands would have to be used; however, the combined use of at least 25% of lands in the two regions would also meet the 2M tDM threshold. The combined use of only 5% land across all land classes in Ontario would also achieve the same result, assuming 100% biomass recovery. If all tillable land classes were used for producing switchgrass, all Class 5 lands could theoretically supply about 2.5M tDM biomass. Class 4, 3, 2, and 1 land could supply 5.3M, 10.0M, 16.3M and 10.5M tDM biomass, respectively. Using Table 4.1.2, it is possible to create other land use scenarios for switchgrass biomass production through combinations of percentage land planted to switchgrass and land classes within each region, among the regions, and within the entire province to obtain 2 M tDM or above. Further combinations can be observed using the county specific data in Appendix B.

4.1.6 Break-even Analysis for Switchgrass

Although farmers' reasons for switching from growing traditional crops to biomass crops may be diverse (e.g. environmental stewardship; use of fewer farm inputs), their acceptance of biomass crops will probably be determined more by the profitability of these crops relative to existing alternative land uses. Cropland owners would, therefore, switch to producing switchgrass if it provides an economic return that is at least at par with the most profitable conventional crop rotations (i.e. the opportunity cost). However, since both biomass crops are quite new in Canada, little is known about even the costs of producing them at commercial levels, let alone the possible profitability. Therefore, this analysis aims to evaluate the production and harvesting costs of switchgrass, at the farm-gate level, in order to get an idea of the break-even costs of production. In order for a producer to break even in the production of switchgrass, a number of cost factors must be compensated, including costs associated with establishment, N, P and K nutrient replacement, harvest, consisting of swathing and bailing, field transport, storage and land use. These costs were calculated using enterprise budget and background information provided by OMAFRA (2010). Their discussion of the costs is presented below.

Establishment Costs

Establishment costs are estimated at $124.69/ha/yr for a ten year project, using a 5% discount rate (OMAFRA 2010). The establishment costs in this study assume the use of conventional tillage techniques. It is possible that, in some cases, including stony or steep areas, no-till practice may be preferable, but it may entail less reliable establishment. The costs of weed burn down were estimated at about $74/ha, but, in excessively weedy fields, it may need to be conducted twice, in the fall and spring, doubling these costs. The costs of seedbed preparation were estimated at $109/ha using commercial custom rates, with half of the cost coming from plowing and the other half from cultivating twice. Seeding costs were broken down into three components, including the cost of seed (16.8 PLS/ha at $19.84/kg PLS - $333.33/ha), the cost of start-up fertilizer (45.35kg 6-24-24 @ $800/t - $89.58/ha) and the cost of drill seeding ($46.91/ha). Seed costs are heavily dependent upon demand and supply factors that will likely change if a significant market for switchgrass develops. Despite the fact that no herbicides are currently registered for use on switchgrass in Ontario, annual weed control costs were estimated at $19.75/ha for spraying, $39.50/ha for grass herbicide, $4.94/ha for adjuvant and $22.22/ha for broadleaf herbicide. Mowing was estimated at $41.98/ha based on custom rates. Operating interest was estimated to be $19.53/ha, or half of the operating expense times an interest rate of 5%. An additional cost was also considered, relating to the lack of production in the establishment year and underproduction in the second year. The establishment year land cost was estimated at a minimum rental rate opportunity cost of $74.07/ha/yr. This value could be highly variable, however, depending upon a number of spatial factors, including slope, drainage and opportunity costs. The final establishment cost considered was the establishment failure rate at 10% of the total establishment cost, or $270.35/ha. After totalling the establishment costs for a 10 year time horizon, the total annual establishment costs summed to $389.61. Using a 5% interest rate, the yearly establishment costs (over a ten year time horizon) were estimated to be $124.69/ha/yr, as previously stated (OMAFRA 2010).

Nutrient Costs

While more research is needed to establish the yield response of switchgrass to N application, annual nitrogen costs were estimated using an application of 67.3kg/ha at $1.10/kg pound, giving a result of $74.07/ha. This analysis assumes a fall cut – spring harvest system. A fall harvest has the potential to increase yields, but has an increased P and K cost. The P and K costs are based on a removal rate of 1.81kg P_2O_5/t at $1.21/kg and 1.31kg K_2O/t at $1.21/kg. This puts the estimate of P and K replacement at $29.09. The costs of spreading fertilizer were assumed to be $17.28/ha based on custom rates (OMAFRA 2010).

Harvest, Storage and Opportunity Costs

Swathing costs were estimated to be $41.97/ha, while bailing was estimated to be $8/bale based on custom rates. Field removal and storage costs, which reflect the cost of moving bales from the field to storage, whether in buildings or on skids under a tarp, were estimated to be $50.52/ha. Land costs, which proxy minimum opportunity costs, were estimated to be $74.07/ha (OMAFRA 2010).

A summary of the estimated costs and the subsequent break-even price for switchgrass are presented in Table 4.1.3.

Table 4.1.3: Estimated break-even price of switchgrass production in Ontario.

Annual Costs	**$/ha**	**$/t (@7 t/ha)**	**$/t (@12 t/ha)**
Establishment Costs (Amortized Over 10 Years @ 5%)	124.69	16.28	10.39
N Fertilizer (67.3 kg/ha N @ $1.1/kg)	74.13	9.68	6.18
P & K Removal Fertility Costs (@ $3.80/t)	29.11	3.80	2.43
Fertilizer Spreading	17.30	2.26	1.44
Swathing	42.01	5.48	3.50
Baling ($8/bale)	147.84	19.30	12.32
Field Removal & Storage ($6.60/t)	50.56	6.60	4.21
Land Costs	74.13	9.68	6.18
Total Annual Costs	**559.77**	**79.97**	**46.65**

Source: OMAFRA 2010

Table 4.1.3 puts the break-even price for switchgrass at approximately $79.97/t at 7 t/ha and $46.65/t at 12t/ha. At the lower yield, the break-even is a little bit higher than the crop residue values observed in Section 2, but certainly in the same range. At the higher yield (approximately

1.7 times the lower yield), the price drops to the lower range of the crop residue values in Section 2. Selecting an appropriate cultivar to maximize yield appears to be important in making switchgrass cost competitive with crop residues. Again, it must be reiterated that the breakeven prices are not the market prices set for switchgrass.

4.1.7 Conclusions and Recommendations

The amount of switchgrass biomass that can potentially be produced in Ontario depends on the percentage land class allocated to its production. Our results indicate that the combined use of only 5% of all land classes (Classes 1-5 land) can provide over 2 million tDM biomass, assuming all the biomass were recoverable. Assuming there were only 50% biomass recovery, the use of 10% of all land classes would be enough to meet the threshold biomass volume. At 50% recovery, 25% of Class 2 land would produce more than 2 million tDM switchgrass biomass. Similarly, 40% Class 1 land or Class 2 land or Class 3 land at 50% recovery could meet the 2 million tDM threshold quantity. The combined use of 60% Classes 4 and 5 lands would also meet this minimum target.

Research efforts should be focused on identifying the best cultivars and crop management practices to optimize biomass production for different geographic regions of Ontario. This is especially true given the responsiveness of break-even costs for switchgrass to yield.

SECTION 4.2: BIOMASS AVAILABILITY FROM *MISCANTHUS*

4.2.1. Brief description of Miscanthus (*Miscanthus spp*.)

Miscanthus species are native to Southeastern Asia, China, Japan, Polynesia and Africa, and are currently distributed throughout temperate and tropical areas of the world. Miscanthus is a perennial, warm-season grass that utilizes the C4 photosynthetic pathway. The plant has received widespread attention as a biomass crop in Europe, where it is used primarily for electricity generation by combustion in power plants. Miscanthus benefits include reported rapid growth, promising annual yield, low water and ash contents, and a high energy output to input ratio. In Canada, Miscanthus is being investigated as a biomass crop for combustion and conversion. Although research into Miscanthus production and use has been conducted for more than 15 years in Europe, it is only in its preliminary stages in Canada. Cultivars of *M. sacchariflorus, M. sinensis,* their hybrids, and other Miscanthus species are grown in North America as ornamental crops.

The potential for using Miscanthus as an alternative energy source in Ontario appears to be promising. In side-by-side studies at various locations in Western Ontario, Giant Miscanthus has produced more than double the biomass yield of upland switchgrass per unit area (Samson 2007). However, research on Miscanthus agronomics and crop improvement in Ontario is still in its early stages compared to that of conventional crops; therefore, it is not grown to any great extent in the province. Farmers interested in producing Miscanthus are likely to face similar challenges to those interested in producing switchgrass for biomaterial or biofuel markets. These challenges include finding varieties/cultivars suited to a particular area, making choices related to land-use change and determining the best possible agronomic practices to obtain optimum yields.

The genus *Miscanthus* comprises a group of more than 10 grass species. Many Miscanthus genotypes are sterile hybrids which do not form viable seeds and have to be propagated from rhizomes or plants (Lewandowski et al. 2000; Venturi et al. 1998).

Miscanthus has a growing season in Ontario that begins in late April and is completed by November, when the plant becomes dormant following the first killing frost. Growth each year originates from the buds on scaly rhizomes. Established plants typically reach more than 2 m in height by the end of May and greater than 4 m at the end of each growing season. In established giant Miscanthus plantings, approximately 54 to 107 shoots per square meter are developed. The grass does not flower every year, but when flowering does occur, it takes place in late September or early October. As a sterile hybrid, no viable seeds are produced. As temperatures cool in the fall, the dark green foliage fades to buff and drops, leaving stems (and sometimes sterile flowers at their terminus). Dry matter accumulation increases rapidly during June, July, and August, reaching its maximum dry matter yield in late-summer. Stems are the most commercially important portions of giant Miscanthus and harvesting the dried stems may occur during winter or spring. Harvestable stems resemble bamboo and are usually 1.3 to 2.0 cm in diameter and more than 3 m long.

Miscanthus x giganteus is adapted to a wide range of soil conditions, but is most productive on soils well suited for corn production. Its biomass yield is limited on shallow, droughty, cold, and waterlogged soils Pyter et al. (2009). Biomass production is positively linked to seasonal precipitation and can decline considerably under water-stressed conditions. It may not be adaptable in the northern region of Ontario because of the colder climate there. In North America, *Miscanthus x giganteus* plantings have been established successfully in Ohio, Michigan, Indiana, Illinois and Quebec. Stand failure has been reported for Wisconsin. Miscanthus field trials remain very limited in Ontario.

4.2.2. Current Miscanthus Production Requirements and Methods in North America

Establishment Years

Miscanthus is propagated vegetatively using divided rhizomes, the underground storage organs of the plant (Lewandowski et al. 2000; Venturi et al. 1998). Plant propagation can be performed through plantlets from in-vitro cultivation (micro-propagation), by rhizomes (macro-propagation), or by stem cutting production systems (Atkinson 2009). Longer-term studies comparing micro-propagated plant material with that derived from rhizome showed little difference in establishment rate (>95%), but rhizome-derived plants were taller, while shoot densities were greater for micro-propagated material (Clifton-Brown et al. 2007). In the macro-propagation method, 2-3 year old nursery fields are subjected to 1 to 2 passes by a rotary tiller, which breaks up the rhizomes into 20-100g pieces (Lewandowski et al. 2000). The rhizome pieces are then collected with a potato or flower bulb harvester from nursery fields (Lewandowski et al. 2000). To prevent drying out, the propagules are stored for only a very short time before planting. Compared to rhizomes, micro-propagules are considered to be much more expensive (Atkinson 2009).

To propagate stock in the field, rhizomes that are approximately 10 to 15 cm long and 42 to 60 g are used. Much work still needs to be done on the agronomics of Miscanthus. Currently the planting time in Western and Southern Ontario is mid April through May. The rhizomes are planted approximately 10 cm deep at a spacing of 0.9 m between rows and 0.9 m within rows (approximately 11,984 rhizomes per ha or 4,000 rhizomes per acre) (Pyter et al. 2007). University of Illinois studies have shown that Giant Miscanthus tolerates the application of several pre-emergence and post-emergence herbicides used to control annual grassy and broadleaf weeds (Pyter et al. 2007).

Establishment of a Miscanthus stand can take up to 5 years (Atkinson 2009; Lewandowski et al. 2000). Adequate water is necessary for successful establishment, as well as to optimize production. While it will not withstand continuously waterlogged soils, yield usually increases as more water is available to the crop. Thus, dry soil moisture conditions at, and following, planting may greatly decrease establishment success. Establishment success may also be limited by the death of plants in the first winter after planting. European research suggests new plantings of *Miscanthus x giganteus* may not survive where soil temperatures fall below 3.3°C (26˚F) at a depth of 2.5cm (Lewandowski et al. 2000). However, studies at the University of Illinois indicate that the plant is able to develop leaves that can photosynthesize at temperatures as low as 10°C and stands at research sites in Illinois planted nearly 20 years ago have survived winters with periods below –23°C without loss (Pyter et al. 2007). *M. sinensis* and *M. sacchariflorus* plantings have overwintered the first year in northern Europe where air temperatures have been as low as –18°C (0˚F). Fertilizers are not needed in the first two years of establishment, but maintenance fertilizer rates are required in later years.

In Illinois trials, at seven sites, it was reported that establishment was slowest at the two least fertile sites and that maximum yields are obtainable within three years on fertile soils, but may require 4 to 5 years on poor soils (Pyter et al. 2007). Also, not all rhizomes will sprout and this will require re-planting in year two or three. Some studies have noted that many of the planted rhizomes do not emerge within the first year, either due to very low temperatures during the first winter or poor rhizome quality (Lewandowski et al. 2000). Delayed emergence of plants in the first year can cause a delay in establishment. A stand density of 10,000 plants/ha is considered optimal to maximize yield (Atkinson 2009). Following establishment, Giant Miscanthus appears to be remarkably efficient at capturing and retaining nitrogen. In European trials, there was no significant effect of nitrogen fertilization on yield (Lewandowski et al. 2000). Yield reductions were not observed even at sites where no nitrogen had been applied. However, more fertility studies in Ontario are needed and are ongoing so that yields can be optimized through proper fertilization. Preliminary Ontario studies do indicate a response to added nitrogen.

Production Years

Unlike other cash crops, a stand of Miscanthus is believed to remain productive for 15–20 years (Lewandowski et al. 2000; Khanna et al. 2008). However, the actual productive life of a stand of Miscanthus is unknown in North America and very few studies have been conducted in North America to monitor the long term productivity of the plant. Such long term studies have been conducted in Europe (Clifton-Brown et al. 2007; Christian et al. 2008), where soil, temperature and weather conditions are different from those in Canada. It is, therefore, difficult to predict the productivity of a stand of Miscanthus in Ontario. In this study, we assume that the productive life of a stand of Miscanthus is 20 years (Khanna et al. 2008; Lewandowski et al. 2000; Lewandowski et al. 2003; Bullard et al. 2004; Heaton et al. 2003) and that the plant will be fully established in the first 3 years. We further assume that once the stand is completely established, by the end of the third year, its peak yield is expected to stay the same until year 20 (Huisman et al. 1994; Huisman et al. 1997; Lewandowski et al. 2000; Lewandowski et al. 2003; Khanna et al. 2008).

While the majority of the trials in the European Union have involved clones of *M. x giganteus*, other genotypes have also been evaluated. The general observation in the selection of cultivars has been that, in northern cooler regions (as in Canada), *M. x sinensis* appears to be better adapted than *M. x giganteus*, due to the former cultivar's higher cold tolerance (Heaton et al. 2003).

Production Years: Fertilization & Weed Management

Fertilizer application rates reported in the literature vary widely. Particularly, nitrogen fertilizer application rates are uncertain, since there is no consensus on the yield response of Miscanthus to nitrogen fertilization (Smeets et al. 2009; Lewandowski et al. 2000). However, the plant's use and conservation of nitrogen imply that once the crop is established, it will require relatively low annual rates to support growth. Table 4.1.2 lists the various rates of fertilization used in different studies.

Table 4.2.1: Fertilizer application during production years after establishment of Miscanthus rhizomes

Study	Fertilizer		
	N	**P**	**K**
Khanna et al. 2008	50 kg/ha	0.3 kg/t DM	0.8 kg/t DM
Lewandowski et al. 2000	60 kg/ha	0.3 – 1.1 kg/t DM	0.8 – 1.2 kg/t DM
Huisman et al. 1997	75 kg/ha	50 kg/ha	100 kg/ha
Heaton et al. 2003	80 kg/ha	10 kg/ha	60 kg/ha
Clifton-Brown. 2001	60 kg/ha	44 kg/ha	110 kg/ha
Himken et al. 1997	60 kg/ha	8 kg/ha	80 kg/ha

Weed control is very important for rapid establishment. Labelled herbicide choices are, however, currently limited and none is registered for use in Ontario. Pre-emergence and post-emergence herbicide combinations safely applied to Giant Miscanthus in 2006 studies in Illinois (Pyter et al. 2007) included: Pendimethalin and 2,4-D ester; Pendimethalin and dicamba; Pendimethalin/atrazine and 2,4-D ester; Pendimethalin/atrazine and dicamba; and S-metolachlor/atrazine and 2,4-D ester. Similar studies in Ontario are still ongoing.

Production Years: Harvesting and Yields

Currently, there are few commercially available mechanical planters or harvesters specifically designed to work with Giant Miscanthus in North America, although efforts are being made to develop new equipment to mechanize most of the crop's production operations. In Europe, potato planters and harvesters have been successfully modified for Giant Miscanthus rhizomes. In addition, a British company has developed a mechanical planter specifically for Giant Miscanthus rhizomes (www.bical.net). Stems have been harvested using hay mowers and balers. In some cases, the stems are chopped at harvest, while they are baled for storage in other settings. A majority of the studies in Europe suggest that Miscanthus should be harvested during the spring (February–March) because this improves the combustion quality of the harvested biomass. Preliminary findings from the research trials in Illinois confirm this finding (Khanna et al. 2008). By allowing the crop to stand in the field for an extended period, the nutrient and moisture content of the harvested biomass is reduced, making it more compatible for combustion; however, there is a trade-off, since biomass yield decreases as well (Smeets et al. 2009). Lewandowski et al. (2000) reported an average yield loss of 35.5% due to delayed harvest. Lewandowski et al. (2000) also showed the decrease in mineral contents when harvesting was delayed from November to January (Table 4.2.2). In general, late winter or spring harvests result in a higher quality feedstock for combustion, but lower yields. Research in Europe and Illinois shows a 30 to 50 percent yield reduction when harvest is delayed from fall to late winter or early spring.

Table 4.2.2: The impact of delayed harvesting on the mineral and carbohydrate content of Miscanthus (Lewandowski et al. 2000)

Mineral content (% dry matter)	Harvest date	
	19th November 1997	29th January 1998
N	0.47	0.36
P	0.06	0
K	1.22	0.96
Cl	0.56	0.09
Sugars	0.3	2.07
Starch	0.7	0.14

A wide range in yield exists for Miscanthus and this has been attributed to the dependence of the yield potential of Miscanthus on its genotype, as well as the climatic/weather conditions under which it is grown (Lewandowski et al. 2000; Khanna et al. 2008). For example, in Illinois studies reported by Khanna et al. (2008), yields have varied depending on the crop age and the weather during the growing season. At three Illinois sites in replicated studies, the end-of-season biomass yields of unfertilized giant Miscanthus, planted in 2002, averaged over a 3-year period after establishment (2004- 2006), were 23.7 tDM/ha in Northern Illinois, 37.5 t DM/ha in Central Illinois, and 44.0 tDM/ha in Southern Illinois. In the same three-year period, yields for unfertilized upland switchgrass, 'Cave in Rock', seeded in 2002, were 6.2 tDM/ha in Northern Illinois, 14.8 tDM/ha in Central Illinois, and 7.7 tDM/ha in Southern Illinois. In general, the dry matter yield of Miscanthus in the establishment year is less than 3 tDM/ha, which is insufficient to merit harvest. Research in Europe has shown dry matter yields of 10 to 24.6tDM/ha in non-irrigated, fully-established Miscanthus, with average yields of 18.8tDM/ha. Research in Illinois has resulted in 22.4-33.6 tDM/ha with tonnage decreasing at more northerly latitudes.

While planting densities in the various studies range from 1-4 plants/m^2, they do not have a large effect on the final yield. Jørgensen et al. (1997) noted that yield at different planting densities level out some years after establishment. In this study, we assumed an average peak yield of 11.14 tDM/ha at spring harvest in Ontario.

4.2.3. Constraints and Limitations in Miscanthus Production and Procurement

Constraints and challenges in Miscanthus production and procurement could hamper the large scale production of the crop in Ontario. Such challenges may include finding varieties/cultivars suited to a particular area, making choices related to land-use change, determining the best possible agronomic practices to obtain optimum yields, farm-level storage issues, weed control and biomass quality issues related to combustion. There is also a lack of highly qualified people to advise producers on the production of these species.

Finding Suitable Varieties/Cultivars

One Miscanthus genotype or energy crop type may not be a good performer in all areas of Ontario. Khanna et al. (2008) provides a good example of the performance of a cultivar or genotype at different geographic regions. Different cultivars of Miscanthus or switchgrass would perform at optimum depending on the climatic and soil types of a particular geographic region. In a similar study in Denmark by Jørgensen (1997), the results indicated that variation in average dry matter yield over three years of measurements at spring harvest was 8.9 tDM/ha for *M. sinensis* selections and 7.7 tDM/ha for *M. giganteus*. The need to find cultivars suitable for every ecological region, thus, becomes very important. The genotypic variation found in Miscanthus can be used in a breeding program to create genotypes to match different climatic conditions and to produce biomass of specific qualities. However, constraints exist in this area due to patent issues associated with Miscanthus material ownership.

Weed Competition

Miscanthus is not a good competitor against weeds during the establishment period and this may pose a problem in the crop’s production (Huisman et al. 1997). However, once the plant is established, leaf-litter ground cover and rapid canopy closure are able to suppress weed growth (Styles et al. 2008). Quantity and characteristics of control depend on the weeds in the field. Atrazine and 2,4-D are recommended for pre-establishment weed control at 3.52 L/ha and 1.75 L/ha, respectively.

Harvest Losses

A major constraint in Miscanthus procurement revolves around its post-harvest losses in storage. There are a number of issues associated with biomass storage, at the farm-gate level, prior to its delivery to aggregators/processing plants. During storage, biomass can change its moisture content, energy value and dry matter content due to degradation processes (microbiological activity) (Wihersaari 2005). The storage conditions can have considerable influence on biomass properties essential for its energy use (Hunder 2005). The temperature in a biomass pile rises as the material starts to decay, leading, in extreme cases, to self-ignition and potential fire (Hunder 2005). Decomposing of biomass material also leads to material and energy losses. The change in temperature of a biomass pile is dependent on the moisture content of biomass, where, in general, the higher the initial moisture content of the stored feedstock, the higher the dry matter losses. Temperature changes in a biomass pile can also be influenced by the size of the stored biomass. Since moisture content and biomass size influence its energy content, various pre-treatments (e.g., pelletizing, drying or chipping) could help stabilize biomass properties in relation to potential changes in its energy content during storage (Wihersaari 2005). However, the more sophisticated the storage conditions provided, the higher the necessary investment in infrastructure (Wihersaari 2005).

Combustion Quality Issues

The chemical composition of a Miscanthus genotype may have different levels of relatively high mineral contents, which can reduce its quality for combustion. The results of Jorgensen (1997) indicated large variations in concentrations of N, K and Cl in 15 selections of the species *M. sinensis*, and *M. giganteus*. The study also reported large variations in yield and mineral concentrations within the selections of *M. sinensis*. K and Cl content decreased more in *M. sinensis* than in *M. giganteus* at winter harvest. In the Danish climate, only *M. sinensis* flowers and shows physiological senescence, while *M. giganteus* stays in the vegetative stage until it is killed by the frost. This is probably part of the reason for the difference between genotypes in K and Cl lability

As stated earlier, several studies suggest that Miscanthus should be harvested during the spring to improve the quality of the harvested biomass. By allowing the crop to stand in the field for an extended period, nutrients such as K and Cl are translocated to the storage organs in the soil thus making the harvested biomass more compatible for combustion. However, spring harvests can be problematic, if the ground is wet during delayed harvest, leading to dirt tagging. Harvest damage to new growth before the removal of the old shoot can also be problematic.

Environmental/Sustainability Issues

There has been public concern of the possibility of Miscanthus becoming a weed on arable lands. However, Miscanthus produces only sterile seeds (Scally et al. 2001) and this property limits its capacity to spread unintentionally from seed. In addition, the rhizome structure of giant Miscanthus spreads very slowly, which minimizes vegetative spread. The oldest research stands in Europe were planted in the late 1980s and have only moved approximately 3 feet from their original location (Jørgensen 1997). To reduce the risk of spread to and from agricultural lands, it is recommended that any new genotypes developed in the future be sterile (e.g., triploid) as a precaution against them becoming weeds. In Ohio and Indiana (USA), there have been reports of some small-scale escapes of fertile ornamental Miscanthus genotypes, which have caused local concern (Khanna 2009), reinforcing the case for releasing only sterile hybrids of Miscanthus.

The greenhouse gas balance for Miscanthus has been generally found to be quite positive (Styles and Jones 2007; Lewandowski et al. 1995). One of the major drivers for growing Miscanthus is its potential for the reduction of Green House Gas (GHG) emissions. Two major mechanisms by which growing Miscanthus (and switchgrass), as a source of renewable energy, can offset carbon emissions include carbon mitigation and carbon sequestration. Regarding carbon mitigation, Miscanthus is a carbon neutral fuel as the carbon that is released during its combustion has been absorbed by the plants when they were growing. Thus, there is no net increase in CO_2 into the atmosphere. Furthermore, greenhouse gas emissions from Miscanthus cultivation will be lower than those from other agricultural activities, largely due to lower amounts of fuel and fertilizer usage and the absence of animal related emissions. Miscanthus can also sequester carbon, preventing its release into the atmosphere. Sequestration occurs when the inputs of carbon dioxide are greater than removals from harvesting and decomposition. Carbon is stored in the rhizomes and roots of Miscanthus as well as in un-harvested stubble. Experiments conducted in Ireland have shown that Miscanthus can store 8.8 tonnes of carbon per hectare in its roots and rhizomes 12 years into its life (Caslin et al. 2010).

Like switchgrass and other perennial grass species, Miscanthus offers several conservation benefits compared to conventional annual row crops and, as such, becomes more suitable in some regions and on some landscapes (Blanco-Canqui 2010). For example, Miscanthus stands provide habitat for wildlife for longer periods of time during the growing season compared to annual grain crops. Two independent studies in Europe indicated that Miscanthus seemed to provide a habitat which encourages a greater diversity of species than cereal crops (Caslin et al. 2010). The lesser use of pesticides in Miscanthus production also reduces impact on other species. By virtue of their perennial nature, both Miscanthus and switchgrass reduce the frequency of, and potential degradation associated with, tillage. These crops also capture solar radiation for a longer portion of the year compared to annual species (Baker et al. 2007).

To date, there are no reports of plant diseases significantly limiting production, although the crop is known to be susceptible to *Fusarium* blight and that may present a significant risk (Walsh and McCarthy 1998). There are also no registered pesticides for Miscanthus currently. Fertiliser requirements and potential for leaching are low and there are few negative impacts on soil quality (Lewandowski et al. 2000).

4.2.4. Competing Uses of Miscanthus Biomass

Current and prospective uses of Miscanthus biomass are the same as for switchgrass, as summarized in Table 4.1.1. Currently, the use of Miscanthus is very limited since the crop is new to Canada, but competing prospective uses of Miscanthus may include feed and bedding for livestock, insulating material in the building industry, particle board, paper, chemicals, fibre in biocomposites for the automotive and building industries, bioethanol production, and electricity and heat generation.

4.2.5. County Level Assessment of Miscanthus Biomass Availability

Miscanthus production in Ontario is even more recent than that of switchgrass. Thus, there is an even less distribution of field trials on this crop compared to switchgrass. Indeed, so far, data from Ontario studies on Miscanthus yields are limited to the establishment period only. Most of the reported post-establishment yield studies are of European origin (Clifton-Brown et al. 2001; Kristensen 2001; Jørgensen 2000) and the conditions under which those yields were obtained are completely different from the Ontario context. Using a simulation approach, Khanna et al. (2008) estimated Miscanthus yields across Illinois, USA. Various yield estimates from other parts of the US with similar conditions have also been reported elsewhere by other researchers (Pyter et al. 2007). Studies are currently being conducted in Ontario on field plots in Guelph, Elora, Simcoe, Ridgetown, Kemptville and Leamington to determine which Miscanthus genotypes have the best yields and survival rates under Canadian weather. Since that study is currently incomplete, this study does not assume any one specific type of Miscanthus, but assumes the mean yield of 11.14 tDM/ha. This yield is based on a spring harvest on the "very high valued lands" (Classes 1, 2 lands), 10.03 tDM/ha on Class 3 land (i.e., 90% of the productivity of very high valued lands), 8.9 tDM/ha on Class 4 land (i.e., 80% of the productivity of very high valued lands), and 7.8 tDM/ha on Class 5 land (i.e., 70% of the productivity of very high valued lands). These assumed yield values may be conservative for the high valued lands and less conservative for the marginal lands. Based on these assumptions, similar to the case of switchgrass, the following five scenarios for Miscanthus production in Ontario were created: (1) 5% land use; (2) 10% land use; (3) 25% land use; (4) 60% land use; and (5) 100% land use. Potential county-based biomass production results were aggregated into regional production. Individual county production is presented in Appendix B. As in the case of switchgrass, each scenario is aimed at meeting at least the annual biomass requirement target of 2M tDM biomass, assuming 100% biomass recovery at harvest. The results of these scenarios are summarized in Table 4.2.3.

Table 4.2.3: Estimated amount of Miscanthus biomass by percentage of land class allocated to Miscanthus production (tDM/yr)

Land Class	***Land Planted to Miscanthus***				
	5%	**10%**	**25%**	**60%**	**100%**
			Southern Ontario		
1	147,984	295,968	739,920	1,775,808	2,959,679
2	550,637	1,101,274	2,753,185	6,607,645	11,012,741
3	260,718	521,435	1,303,587	3,128,608	5,214,347
4	22,265	44,530	111,326	267,181	445,302
5	21,909	43,818	109,544	262,905	438,176
ALL	**1,003,513**	**2,007,025**	**5,017,562**	**12,042,147**	**20,070,245**
			Western Ontario		
1	507,744	1,015,487	2,538,717	6,092,920	10,154,867
2	223,172	446,344	1,115,860	2,678,064	4,463,440
3	180,652	361,303	903,257	2,167,816	3,613,026
4	61,521	123,041	307,603	738,246	1,230,410
5	91,744	183,488	458,721	1,100,930	1,834,883
ALL	**1,064,832**	**2,129,663**	**5,324,158**	**12,777,976**	**21,296,626**
			Central Ontario		
1	99,524	199,047	829,363	1,990,471	3,317,451
2	58,960	117,920	491,335	1,179,203	1,965,338
3	60,107	120,214	500,892	1,202,141	2,003,569
4	49,835	99,670	415,291	996,700	1,661,166
5	33,465	66,929	278,869	669,286	1,115,476
ALL	**301,890**	**603,780**	**2,515,750**	**6,037,801**	**10,063,000**
			Eastern Ontario		
1	17,059	34,118	85,296	204,710	341,183
2	200,442	400,884	1,002,209	2,405,302	4,008,836
3	166,229	332,457	831,141	1,994,739	3,324,565
4	109,522	219,044	547,610	1,314,265	2,190,441
5	40,780	81,560	203,901	489,361	815,602
ALL	**534,032**	**1,068,063**	**2,670,157**	**6,408,377**	**10,680,627**
			Ontario Total		
1	772,310.00	1,544,620	4,193,296	10,063,909	16,773,180
2	1,033,211	2,066,422	5,362,589	12,870,214	21,450,355
3	667,705	1,335,409	3,538,877	8,493,304	14,155,507
4	243,143	486,285	1,381,830	3,316,392	5,527,319
5	187,898.00	375,795	1,051,035	2,522,482	4,204,137
ALL	**2,904,266**	**5,808,531**	**15,527,627**	**37,266,301**	**62,110,498**

If all tillable land considered in this analysis (i.e., 100% of Classes 1-5 lands) were used, the combined production of all the regions would amount to over 60M tDM Miscanthus biomass. The largest potential biomass supply is obtainable in the Southern and Western Ontario regions. Using only 10% of the land in either Southern or Western Ontario for producing Miscanthus exceeds the annual target biomass of 2M tDM and the combined use of only 5% of the land in the two regions would also meet the target. Use of all of the Class 1, 2 or 3 lands in either of these two regions would also meet the 2M tDM threshold. If only 25% of Class 2 lands in the Southern Ontario region, or 60% of the Class 1, or 2 or 3 lands in Western Ontario, were used, the required threshold volume of biomass would also be attained. Similarly, in Central and Eastern Ontario, 25% use of all land classes would also meet the required biomass target. The combined use of 5% of all land classes in Ontario would exceed the 2M tDM target, assuming 100% biomass recovery. All of the Class 5 lands in Ontario could theoretically supply about 4.2M tDM biomass; similarly, all Class 4, 3, 2, and 1 lands could supply 5.5 M, 14.15 M, 21.4M and 16.7M tDM biomass, respectively. Thus, if there were only 50% biomass recovery at harvest due to harvest equipment efficiency or other harvest constraints, all of the Class 5 lands could still supply over 2M tDM Miscanthus biomass.

Using Table 4.2.3 and Appendix B, a multitude of other biomass productivity scenarios can be created through combinations of percent land planted to Miscanthus and land classes within each region, among the regions, and within the entire province, to obtain any feasible biomass productivity target, including the 2M tDM target.

4.2.6. Break-even Analysis for Miscanthus

To determine the cost of growing Miscanthus in Ontario, an enterprise budget similar to that of Khanna et al. (2008) was developed. The budget estimates the cost per tDM of producing Miscanthus. As stated earlier, this study does not assume any one specific Miscanthus genotype; all costs in our break-even analysis are calculated for a generic Miscanthus stand. The costs include establishment, fertilizer application, weed control, harvesting, broken down into swathing, raking and baling, and the costs of farm-gate level storage.

Establishment Costs

For the purposes of this analysis, we assumed that rhizomes were bought from an external source and were not produced on the farm. The price of a rhizome reported in the literature in North America varies from \$0.03 to more than \$0.60 (Smeets et al. 2009, Khanna et al. 2008). Khanna et al. (2008) estimates a price of \$0.034 per rhizome. This study assumed a price of \$0.315 per rhizome, since this is the mean value of the price range \$0.03 per rhizome and \$0.60 per rhizome.

Tillage operations precede rhizome planting. The costs of primary and secondary tillage for this study were determined based on the 2006 Custom rental rates from the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Primary tillage costs equal \$35/ha and secondary tillage costs equal \$15/ha. Replanting of Miscanthus rhizomes can be done using a rhizome planter and the literature outlines multiple types of rhizome planters, many of which are customized versions of existing machinery (Huisman et al. 1997; Venturi et al. 1998). Since there are no rhizome planters in Canada, the cost of the planter is estimated based on the cost of a potato planter (Khanna et al. 2008; Huisman et al. 1997; Lewandowski et al. 2003). The cost of planting one hectare of Miscanthus rhizomes using a potato planter is estimated to be \$75.75 (Lazarus et al. 2005). The rhizomes are planted at a density of 1 plant/m^2. In the literature, planting densities range from 1 to 4 plants/m^2 (Venturi et al. 1998; Heaton et al. 2003). Advantages of a higher planting density include a higher yield in the first 2-5 years, but as this yield increase does not compensate for higher planting costs, a density of one plant per square meter is recommended (Lewandowski et al. 2003). The cost of planting a hectare of field with Miscanthus rhizomes at a density of 1 plant/m^2 at the price of \$0.315/rhizome is equal to \$3150/ha.

Costs of Fertilizing

Considering the information in Table 4.2.1, this study assumed the following application rates - 60 kg N/ha applied in year one and 50 kg N/ha applied in year two onwards (post-establishment). Phosphorous and K were only applied year 2 onwards at the rate at which they were removed from the soil by the plant. From Khanna et al. (2008) and Lewandowski et al. (2000), application rates of 0.3 kg/tDM for P and 0.8 kg/tDM for K were used. The cost of nitrogen was calculated based on the price of nitrogen solution (UAN) 28% (\$372.87/t), while

UAN is a liquid and a farmer may use another fertilizer for N, UAN just provides a cost estimate. The cost of phosphorous was calculated using the price for triple superphosphate 0-46-0 ($725.74/t) and the cost of potassium was calculated using the price of Muriate of Potash 60% ($559/t). All prices were taken from the Ontario Farm Input Monitoring project (McEwan 2009). A five year average was used for all three fertilizers. The final costs for nitrogen was $112.02 N/ha in year 1 and $93.35 N/ha from year 2 onwards. The costs for P and K varied depending on yield. The cost of fertilizer application using a fertilizer spreader was $17.5/ha (OMAFRA 2006).

Costs of Weed Control

Herbicide application is only required during the establishment phase (Smeets et al. 2009; Huisman et al. 1997; Styles et al. 2008). During the establishment period, Miscanthus is not yet a good competitor against weeds (Huisman et al. 1997). However, once the plant is established, leaf-litter ground cover and rapid canopy closure are assumed to suppress weed growth (Styles et al. 2008). Quantity and characteristics of control depend on the weeds in the field. To estimate herbicide costs, application rates estimated by Khanna et al (2008) were used. During the pre-establishment period, 3.52 L/ha of Atrazine and 1.75 L/ha of 2,4-D were applied. The prices of herbicides were based on the Ontario Farm Input Monitoring project (McEwan 2009). The price of the herbicides was averaged over five years (2005 to 2010). The price of atrazine was $7.30/L and the average price of 2,4-D over the same period was $8.09/L. The total herbicide cost equalled $39.83/ha ($25.68 atrazine plus $14.15 2,4-D). The cost to apply the herbicides using a self propelled applicator was taken from OMAFRA's Custom rental rate survey of 2006. However, there is currently no registered Atrazine rates for Miscanthus in Canada; therefore the above rates may not apply under Ontario conditions.

Harvesting Costs

Harvesting can be done when the crop has senesced. However, delaying harvest until spring is a common practice since this improves the combustion quality of the harvested biomass. In this analysis, we assumed spring harvest and also assumed that the harvesting operations of Miscanthus include swathing, baling, farm-gate level loading and unloading, and storage. A conventional harvester and baler are assumed to be used.

Cost estimates for this study are based on Miscanthus being swathed and then baled. Swathing costs are estimated to be $37.5/ha and raking cost are estimated to be $15/ha (OMAFRA, 2006). Both costs could be underestimated since they are based on the cost of producing hay, which has 30-40% less yield than Miscanthus. To calculate the cost of baling Miscanthus, this study used the cost of production budget for hay available from OMAFRA (2007). It was assumed that large square bales with a density of 218 kg/m3 would be produced and each bale would weigh 334 kg (OMAFRA 2006). This would allow 3 bales to be produced from each tonne of Miscanthus. With an assumed yield of 11.14 tDM/ha, 41.79 bales would be produced per hectare. The cost per bale is $7 and, therefore, the total cost of baling one hectare of Miscanthus (at peak yield) equalled $292.53 (OMAFRA 2006). The bales would then be transported to the storage facility at a price of $1.37/bale, which includes loading the bales onto a truck, transporting the bales to the storage facility and then unloading the bales (OMAFRA 2006). The total cost of transferring 11.14 tDM of Miscanthus (i.e., 41.79 bales) from the field to storage is $57.25.

Storage

To ensure year round availability of biomass for heating, it is important to consider the costs of storage. Storage of Miscanthus would depend on the harvest method used. Standard methods for straw or hay can be used for collecting and handling Miscanthus bales for transport and storage. For handling chopped material, methods similar to those of maize silage can be applied (Lewandowski et al. 2000). Several storage methods are available, including storage in open air without covering, storage in open air, covered with plastic sheeting or organic material, and storage in existing or new farm buildings.

The cheapest and most used option is storage in the open air with plastic sheeting (Huisman et al. 1997). Storage in new buildings is prohibitively expensive and storage in open air is problematic due to loss of biomass from decay (Huisman et al. 1997). This assumes storage in open air, covered with plastic sheeting. The cost of this storage is included in the harvesting cost and amounts to $3.60/bale (OMAFRA 2006).

Discount Rate

Considering that a Miscanthus enterprise could last up to 20 years, the costs and revenues of the enterprise need to be discounted to determine the Net Present Value (NPV). Since the market price for Miscanthus in Canada is currently unknown, estimating revenues is difficult. To overcome this unknown, the delivered yield (yield after field and storage loss) was used as a proxy for revenue and was discounted to arrive at the break-even price of Miscanthus. Usually, the discount rate for an enterprise is determined by its level of riskiness, where the riskier the enterprise the higher the discount rate. Khanna et al. (2008) used a discount rate of 4%, Styles et al. (2008) used a discount rate of 5% and Huisman et al. (1997) used a discount rate of 7% to calculate their NPV. However, since the market for Miscanthus has not yet been established in Ontario, there is greater uncertainty for Miscanthus growers. Thus, a discount rate higher than 4% may be necessary. In this study, we assumed a base case discount rate of 5% to calculate the NPV. Table 4.2.4 summarizes the enterprise budget for Miscanthus in Ontario.

Table 4.2.4: Enterprise Budget for Miscanthus at 11.19 tDM/ha

Item	Year 1	Year 2	Years 3 - 20	Sum (20 yrs)
Planting material Costs				
Rhizomes ($/ha)	$3,150.00	$0.00	$0.00	$3,150.00
Establishment Costs				
Primary Tillage ($/ha)	$35.00	$0.00	$0.00	$35.00
Secondary Tillage ($/ha)	$15.00	$0.00	$0.00	$15.00
Planting ($/ha)	$75.75	$0.00	$0.00	$75.75
Herbicide Costs				
2,4 – B ($/ha)	$14.16	$0.00	$0.00	$14.16
Atrazine ($/ha)	$25.70	$0.00	$0.00	$25.70
Herbicide application equipment ($/ha)	$20.00	$0.00	$0.00	$20.00
Fertilizer Costs				
Nitrogen ($/ha)	$22.20	$18.50	$18.50	$373.70
Phosphorous[1] ($/ha)	$0.00	$3.28	$6.56	$121.36
Potassium[1] ($/ha)	$0.00	$5.18	$10.36	$191.73
Fertilizer spreader ($/ha)	$17.50	$17.50	$17.50	$350.00
Harvesting Costs				
Swathing/ Conditioning ($/ha)	$0.00	$37.50	$37.50	$712.50
Raking ($/ha)	$0.00	$15.00	$15.00	$285.00
Baling[1] ($/ha)	$0.00	$146.27	$292.53	$5,411.81
Load, transport, unload[1] ($/ha)	$0.00	$28.63	$57.25	$1,059.17
Storage[1] ($/ha)	$0.00	$75.22	$150.44	$2,783.21
Total cost ($/ha)	**$3,375.31**	**$346.08**	**$605.64**	**$14,624.09**

[1]Costs change with yield of Miscanthus stand

From Table 4.2.4, the total twenty year cost for a Miscanthus stand has been established at \$14,624.09/ha. Using a 5% discount rate, the net present value of the stream of costs presented is equal to \$9,949.97/ha. Given a total yield of 207.3 t/ha (total yield of 20 years), the break-even cost for Miscanthus is \$48.00/t. This value puts Miscanthus break-even prices in a similar range compared to switchgrass and crop residues. However, depending on the yield of switchgrass, Miscanthus could provide more cost-effective option for producing biomass, providing that the estimated yields from more southern climates can be established in Ontario.

4.2.7. Conclusions and Recommendations.

The annual amount of Miscanthus biomass that can potentially be produced in Ontario depends on the percentage land class allocated to its production and the yield potential on the various land classes. The results indicate that the combined use of only 5% of all land classes (Classes 1-5 land) can provide almost 3 million tDM biomass. Assuming only 50% biomass recovery, the use of 10% of all land classes would be enough to meet the threshold volume. At 50% recovery, 25% of all tillable land in either Southern Ontario or Western Ontario could also meet and surpass the 2 million tDM biomass target. Similarly, at 50% recovery, 60% of all tillable land in Central Ontario or Eastern Ontario could meet the threshold quantity, as would the combined use of 10% of all lands in Southern and Western Ontario. In summary, the potential land base for producing Miscanthus biomass (or switchgrass) in Ontario is adequate to meet and surpass the 2 million tDM threshold biomass quantity for this study. Furthermore, the land base could be able to meet the needs of other competitive uses without seriously affecting the production and supply of conventional food crops.

Research efforts should be focused on identifying the best Miscanthus cultivars and crop management practices to optimize biomass production for different geographic regions of Ontario. As long as Miscanthus yields approach those estimated in this study, it likely provides a cost-effective biomass production alternative compared to switchgrass. Nonetheless, it appears to be in the same cost range as switchgrass and crop residues.

SECTION 5: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This study aims to assess the farm-level economic feasibility and the sustainable availability of biomass from four crop residues (corn stover, soybean and wheat straws, and corn cobs) and two dedicated cultivated, biomass crops (switchgrass and Miscanthus) in common rotation scenarios in Ontario.

The results of our analysis suggest that the possibility of crop residue removal in Ontario is feasible, and worth the effort in only limited locations, which we refer to in the study as 'qualified lands'. Soil organic matter (SOM) maintenance was selected as the constraint to determine the sustainable availability of each biomass option and four scenarios for each region defined by the rate at which SOM is formed from non-grain biomass produced in common rotation scenarios and the rate at which existing SOM is decomposed. Under typical SOM formation and decomposition conditions and assuming a typical and common corn-soybean-winter wheat (CSW) rotation scenario, about 1.1M tDM of crop residue could be sustainably removed each year, primarily from the major agricultural counties in the province. Treated separately from the other residues, about 0.83M tDM corn cobs can be procured annually across Ontario. Annual sustainable residue removal will depend on soil type, topography and climatic conditions; however, the removal also depends crucially on crop management practices that increase soil carbon input. Such practices include the complexity of crop rotation, conservation tillage, the use of cover crops with prolific rooting systems and vegetative growth in rotations, adding animal and/or green manure or compost to field crops, and adding soil amendments that can increase both the active and heavy fractions of SOM.

Instead of crop residue, dedicated biomass crops such as Miscanthus and switchgrass could be used for biomass production since both species have been reported to produce high yields with relatively low nutrient addition. Potential biomass productivity in each county of Ontario was determined by assuming percentages of the area of tillable land by quality that could be allocated to these crops. The use of only 5% of all tillable land classes (i.e. Classes 1-5 lands) can provide over 2M tDM of either switchgrass or Miscanthus biomass assuming all above ground biomass is recoverable. Assuming a 50% biomass recovery due to harvesting inefficiency and/or other technical constraints, and without considering the practicality of biomass procurement, the following scenarios can also meet a 2 M tDM yield goal without taking into account the economic costs that may be involved in biomass harvesting and its transportation to the aggregator:

- 10% of all tillable land classes (i.e., Classes 1-5 lands);
- 25% of all tillable land in either Southern Ontario or Western Ontario;
- 60% of combined Classes 4 and 5 lands (see Tables 4.1.2 and 4.2.3).

The break-even price for crop residues is between \$57/t and \$87/t, and for dedicated crops is \$48.00/t for Miscanthus and \$46.65/t to \$79.97/t for switchgrass, respectively. The breakeven costs cover only production and collection costs and do not cover costs associated with risk, management and other financial considerations, such as the costs of decreased SOM resulting from excess removal. These break-even prices represent the minimum price necessary to cover all variable and fixed costs for the farmer but it does not ensure biomass will be supplied at these prices. Simply put, the break-even prices resulting from our analysis are not the prices for biomass. The actual amount supplied for each biomass price depends critically on the opportunity costs associated with not growing typical crops in the conventional manner.

The results of this study suggest that biomass may be more sustainably supplied (and in greater potential quantity) by dedicated perennial deep rooted biomass crops rather than from crop residue removal. Ontario has an adequate land base for producing Miscanthus and/or switchgrass biomass to meet and surpass the need’s suggested by OPG. Furthermore, the Ontario agricultural land base would be able to meet the needs of other competitive uses without significantly affecting the production and supply of conventional food crops. Whether agricultural biomass can be sustainably generated, the actual amount supplied depends on production costs, yields, and opportunity costs of production.

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APPENDIX A1: RESIDUE YIELD FROM AVERAGE AREA HARVESTED BY COUNTY (HI=0.5) BY RESIDUE

County/Division	*Average Area Harvested* ha	*Corn Stover* kg/ha	*Corn Root [Root:Grain Ratio = 1:1]* kg/ha	*Corn Residue* kg/ha	*Soybean Straw* kg/ha	*Soybean Root [Root:Grain Ratio = 1.2:1]* kg/ha	*Soybean Residue* kg/ha	*Wheat Straw* kg/ha	*Wheat Root [Root:Grain Ratio = 1.6:1]* kg/ha	*Wheat Residue* kg/ha
Brant	14717.7	7302.0	7302.0	14604.0	2349.9	2819.9	5169.8	4021.3	6434.1	10455.4
Chatham-Kent	51394.5	8573.8	8573.8	17147.5	2572.0	3086.4	5658.5	4584.3	7334.9	11919.2
Elgin	36450.0	7906.1	7906.1	15812.2	2431.7	2918.1	5349.8	4377.5	7004.0	11381.5
Essex	18054.9	7461.0	7461.0	14922.0	2361.6	2833.9	5195.5	4182.2	6691.5	10873.7
Haldimand-Norfolk	28852.2	7111.3	7111.3	14222.5	2162.8	2595.4	4758.3	3607.7	5772.3	9380.0
Hamilton	8877.6	7015.9	7015.9	14031.7	2174.5	2609.4	4784.0	3734.1	5974.5	9708.6
Lambton	38653.2	8118.1	8118.1	16236.1	2501.9	3002.3	5504.2	4434.9	7095.9	11530.9
Middlesex	56529.9	8149.9	8149.9	16299.7	2537.0	3044.4	5581.3	4676.2	7482.0	12158.2
Niagara Regional	10019.7	6507.2	6507.2	13014.3	2162.8	2595.4	4758.3	3274.5	5239.2	8513.7
Oxford	55517.4	8245.2	8245.2	16490.5	2665.6	3198.7	5864.2	4894.5	7831.2	12725.8
Southern Ontario	319067.1	7945.3	7945.3	15890.6	2438.8	2926.5	5365.3	6884.5	7061.0	13945.4
Bruce	21821.4	6994.7	6994.7	13989.3	2256.4	2707.6	4964.0	7061.9	7243.0	14304.9
Dufferin	3790.8	6549.6	6549.6	13099.1	1952.4	2342.9	4295.3	6470.4	6636.3	13106.8
Grey	5872.5	6433.0	6433.0	12866.0	1975.8	2370.9	4346.7	6111.9	6268.7	12380.6
Halton	4722.3	5956.1	5956.1	11912.1	1894.0	2272.7	4166.7	5574.2	5717.2	11291.4
Huron	66541.5	7906.1	7906.1	15812.2	2572.0	3086.4	5658.5	7384.5	7573.9	14958.4
Peel	3458.7	6401.2	6401.2	12802.4	2057.6	2469.2	4526.8	5986.5	6140.0	12126.5
Perth County	44760.6	7916.7	7916.7	15833.4	2653.9	3184.6	5838.5	7760.9	7959.9	15720.8
Simcoe	19148.4	6687.3	6687.3	13374.7	2045.9	2455.1	4501.1	6327.0	6489.3	12816.3
Waterloo	15608.7	7037.1	7037.1	14074.1	2361.6	2833.9	5195.5	6685.5	6856.9	13542.4
Wellington	24696.9	6856.9	6856.9	13713.8	2268.1	2721.7	4989.7	6846.8	7022.4	13869.2
Western Ontario	210421.8	7388.9	7388.9	14777.8	2356.9	2828.3	5185.2	7042.2	7222.8	14264.9

County/Division	Average Area Harvested (ha)	Corn Stover (kg/ha)	Corn Root [Root:Grain Ratio = 1:1] (kg/ha)	Corn Residue (kg/ha)	Soybean Straw (kg/ha)	Soybean Root [Root:Grain Ratio = 1.2:1] (kg/ha)	Soybean Residue (kg/ha)	Wheat Straw (kg/ha)	Wheat Root [Root:Grain Ratio = 1.6:1] (kg/ha)	Wheat Residue (kg/ha)
Hastings	4390.2	5945.5	5945.5	11890.9	2022.6	2427.1	4449.6	5233.7	5367.9	10601.6
Kawartha Lakes	6164.1	6019.7	6019.7	12039.3	1929.0	2314.8	4243.9	5395.0	5533.3	10928.3
Northumberland	10602.9	6666.1	6666.1	13332.3	2081.0	2497.2	4578.2	5663.9	5809.1	11472.9
Peterborough	3312.9	5648.7	5648.7	11297.5	1882.3	2258.7	4141.0	4893.1	5018.6	9911.8
Prince Edward	4876.2	6252.8	6252.8	12505.6	1952.4	2342.9	4295.3	5502.5	5643.6	11146.2
York	8739.9	6327.0	6327.0	12654.0	1882.3	2258.7	4141.0	5574.2	5717.2	11291.4
Central Ontario	59219.1	6355.6	6355.6	12711.2	1973.5	2368.1	4341.6	5536.6	5678.6	11215.2
Frontenac	1547.1	6602.5	6602.5	13205.1	1999.2	2399.0	4398.2	4899.1	5024.7	9923.9
Lanark	2357.1	6814.5	6814.5	13629.0	2069.3	2483.2	4552.5	4062.7	4166.9	8229.5
Leeds & Grenville	7047.0	6750.9	6750.9	13501.8	2162.8	2595.4	4758.3	5018.6	5147.3	10165.9
Lennox & Addington	2486.7	6136.2	6136.2	12272.5	1742.0	2090.4	3832.3	5036.5	5165.7	10202.2
Ottawa	16078.5	7789.5	7789.5	15579.0	2420.0	2904.1	5324.1	5466.7	5606.9	11073.6
Prescott & Russell	20970.9	7800.1	7800.1	15600.2	2338.2	2805.9	5144.1	4690.0	4810.3	9500.3
Renfrew	3750.3	6528.4	6528.4	13056.7	2127.8	2553.3	4681.1	5332.3	5469.0	10801.3
Stormont, Dundas	43594.2	7959.1	7959.1	15918.2	2420.0	2904.1	5324.1	6026.8	6181.3	12208.2
Eastern Ontario	97831.8	7661.3	7661.3	15322.6	2324.2	2789.0	5113.2	5219.4	5353.2	10572.5
Ontario	700650.0	7595.6	7595.6	15191.2	2373.3	2847.9	5221.2	6814.6	6989.3	13803.8

APPENDIX A2: LAND AREA DISTRIBUTION OF THE TWO ROTATION SYSTEMS, CS & CSW, BY COUNTY

County/Division	*Corn (ha)*	*Soybeans (ha)*	*Wheat (ha)*	*3 Year Limiter*	*3 Year Proportion*	*3 Year Area (ha)*	*2 Year Limiter*	*2 Year Proportion*	*2 Year Area (ha)*	*Unaccounted Corn*	*Unaccounted Soybeans*	*Unaccounted Wheat*
Brant	15366.7	16559.0	5554.0	Wheat	0.9	14995.8	Corn	0.9	18662.6	1036.8	2229.1	555.4
Chatham-Kent	52683.3	90769.0	35754.1	Wheat	0.9	96536.2	Corn	0.9	36908.2	2050.5	40136.2	3575.4
Elgin	37237.0	42258.0	15805.3	Wheat	0.9	42674.4	Corn	0.9	41422.0	2301.2	7322.2	1580.5
Essex	18330.4	74413.0	21768.8	Corn	0.9	49492.1	Corn	0.9	3299.5	183.3	56265.9	5271.4
Haldimand-Norfolk	30202.9	57415.0	12096.5	Wheat	0.9	32660.7	Corn	0.9	34768.8	1931.6	29143.7	1209.7
Hamilton	9214.5	12092.0	3240.1	Wheat	0.9	8748.2	Corn	0.9	11337.1	629.8	3507.4	324.0
Lambton	39432.3	105769.0	41718.4	Corn	0.9	106467.1	Corn	0.9	7097.8	394.3	66731.1	6229.4
Middlesex	58210.8	63589.0	32911.3	Wheat	0.9	88860.5	Corn	0.9	51463.1	2859.1	8237.3	3291.1
Niagara Regional	10340.9	24296.0	6534.9	Wheat	0.9	17644.1	Corn	0.9	8027.1	445.9	14401.1	653.5
Oxford	57174.1	29728.0	16670.1	Wheat	0.9	45009.1	Soybean	0.9	26504.9	28918.6	1472.5	1667.0
Bruce	22551.4	29366.0	13933.9	Wheat	0.9	37621.5	Corn	0.9	18019.7	1001.1	7815.7	1393.4
Dufferin	3964.1	8593.0	4083.6	Corn	0.9	10703.2	Corn	0.9	713.5	39.6	4668.5	515.9
Grey	6222.6	7513.0	3693.5	Wheat	0.9	9972.4	Corn	0.9	5217.3	289.8	1580.2	369.3
Halton	4770.4	8362.0	3362.4	Wheat	0.9	9078.4	Corn	0.9	3139.7	174.4	3766.0	336.2
Huron	67379.2	64524.0	35438.3	Wheat	0.9	95683.5	Corn	0.9	63872.5	3548.5	693.3	3543.8
Peel	3505.3	7184.0	2407.8	Wheat	0.9	6501.1	Corn	0.9	2408.9	133.8	3812.5	240.8
Perth County	45419.1	37266.0	24643.8	Wheat	0.9	66538.3	Corn	0.9	41831.4	2324.0	-5829.1	2464.4
Simcoe	19875.2	28081.0	16162.4	Wheat	0.9	43638.5	Corn	0.9	9592.2	532.9	8738.7	1616.2
Waterloo	16282.6	10649.0	7442.4	Wheat	0.9	20094.5	Corn	0.9	17252.0	958.4	-4675.2	744.2
Wellington	25200.4	30458.0	18080.9	Wheat	0.9	48818.3	Corn	0.9	16069.7	892.8	6150.3	1808.1

County/Division	*Corn (ha)*	*Soybeans (ha)*	*Wheat (ha)*	*3 Year Limiter*	*3 Year Proportion*	*3 Year Area (ha)*	*2 Year Limiter*	*2 Year Proportion*	*2 Year Area (ha)*	*Unaccounted Corn*	*Unaccounted Soybeans*	*Unaccounted Wheat*
Durham	22222.3	15277.0	8752.4	Wheat	0.9	23631.4	Soybean	0.9	13319.7	7685.2	740.0	875.2
Hastings	3540.0	3571.0	1882.8	Wheat	0.9	5083.5	Corn	0.9	3321.9	184.6	215.6	188.3
Kawartha Lakes	6561.0	10054.0	5400.4	Wheat	0.9	14581.0	Corn	0.9	3061.2	170.1	3663.1	540.0
Northumberland	11233.8	10616.0	4942.0	Wheat	0.9	13343.5	Soybean	0.9	11102.7	1234.6	616.8	494.2
Peterborough	3563.6	3585.0	2235.4	Wheat	0.9	6035.6	Corn	0.9	2793.1	155.2	176.6	223.5
Prince Edward	4992.9	7245.0	3989.8	Wheat	0.9	10772.5	Corn	0.9	2523.7	140.2	2392.4	399.0
York	9558.0	9371.0	3958.9	Wheat	0.9	10689.0	Soybean	0.9	10454.4	767.8	580.8	395.9
Frontenac	1675.4	1648.0	261.7	Wheat	0.9	706.6	Soybean	0.9	2542.4	168.6	141.2	26.2
Lanark	2380.8	2464.0	283.3	Wheat	0.9	764.9	Corn	0.9	3826.5	212.6	295.8	28.3
Leeds & Grenville	7205.3	5903.0	134.5	Wheat	0.9	363.1	Soybean	0.9	10407.5	1880.5	578.2	13.4
Lennox & Addington	2525.2	3495.0	2168.5	Wheat	0.9	5854.9	Corn	0.9	1032.5	57.4	1027.1	216.8
Ottawa	16774.7	17056.0	278.3	Wheat	0.9	751.4	Corn	0.9	29743.6	1652.4	1933.7	27.8
Prescott & Russell	21258.4	24009.0	221.5	Wheat	0.9	598.1	Corn	0.9	37906.3	2105.9	4856.5	22.2
Renfrew	3793.4	2317.0	539.6	Wheat	0.9	1456.9	Soybean	0.9	3296.5	1659.6	183.1	54.0
Stormont, Dundas	44809.5	34817.0	728.4	Wheat	0.9	1966.8	Soybean	0.9	61490.5	13408.6	3416.1	72.8

APPENDIX B: SWITCHGRASS AND MISCANTHUS PRODUCTION BY COUNTY

Land Conversion (%)	Switchgrass Supply (t/year) 100	60	25	10	5	Miscanthus Supply (t/year) 100	60	25	10	5
Brant										
Class 1	59,732.5	35,839.5	14,933.1	5,973.2	2,986.6	95,060.0	57,036.0	23,765.0	9,506.0	4,753.0
Class 2	285,261.7	171,157.0	71,315.4	28,526.2	14,263.1	453,973.5	272,384.1	113,493.4	45,397.4	22,698.7
Class 3	235,550.2	141,330.1	58,887.6	23,555.0	11,777.5	337,509.8	202,505.9	84,377.5	33,751.0	16,875.5
Class 4	71,528.9	42,917.3	17,882.2	7,152.9	3,973.8	101,048.7	60,629.2	25,262.2	10,104.9	5,052.4
Class 5	2,935.5	1,761.3	733.9	293.5	183.5	4,088.7	2,453.2	1,022.2	408.9	204.4
Chatham-Kent										
Class 1	176,245.8	105,747.5	44,061.4	17,624.6	8,812.3	280,482.5	168,289.5	70,120.6	28,048.3	14,024.1
Class 2	1,185,592.6	711,355.6	296,398.2	118,559.3	59,279.6	1,886,786.0	1,132,071.6	471,696.5	188,678.6	94,339.3
Class 3	272,156.7	163,294.0	68,039.2	27,215.7	13,607.8	389,961.7	233,977.0	97,490.4	38,996.2	19,498.1
Class 4	1,862.3	1,117.4	465.6	186.2	103.5	2,630.9	1,578.6	657.7	263.1	131.5
Class 5	3,939.4	2,363.6	984.8	393.9	246.2	5,487.0	3,292.2	1,371.7	548.7	274.3
Elgin										
Class 1	149,424.3	89,654.6	37,356.1	14,942.4	7,471.2	237,798.1	142,678.8	59,449.5	23,779.8	11,889.9
Class 2	556,445.5	333,867.3	139,111.4	55,644.5	27,822.3	885,543.2	531,325.9	221,385.8	88,554.3	44,277.2
Class 3	438,517.8	263,110.7	109,629.4	43,851.8	21,925.9	628,333.3	377,000.0	157,083.3	62,833.3	31,416.7
Class 4	14,883.1	8,929.9	3,720.8	1,488.3	826.8	21,025.3	12,615.2	5,256.3	2,102.5	1,051.3
Class 5	9,171.1	5,502.6	2,292.8	917.1	573.2	12,774.0	7,664.4	3,193.5	1,277.4	638.7
Essex										
Class 1	60,341.6	36,204.9	15,085.4	6,034.2	3,017.1	96,029.3	57,617.6	24,007.3	9,602.9	4,801.5
Class 2	949,162.1	569,497.2	237,290.5	94,916.2	47,458.1	1,510,523.6	906,314.2	377,630.9	151,052.4	75,526.2
Class 3	71,011.5	42,606.9	17,752.9	7,101.2	3,550.6	101,749.4	61,049.6	25,437.3	10,174.9	5,087.5
Class 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Class 5	19,820.4	11,892.3	4,955.1	1,982.0	1,238.8	27,607.1	16,564.2	6,901.8	2,760.7	1,380.4
Halmond-Norfolk										
Class 1	98,758.0	59,254.8	24,689.5	9,875.8	4,937.9	157,166.3	94,299.8	39,291.6	15,716.6	7,858.3
Class 2	578,830.7	347,298.4	144,707.7	57,883.1	28,941.5	921,167.7	552,700.6	230,291.9	92,116.8	46,058.4
Class 3	1,026,264.0	615,758.4	256,566.0	102,626.4	51,313.2	1,470,489.7	882,293.8	367,622.4	147,049.0	73,524.5
Class 4	69,192.6	41,515.6	17,298.2	6,919.3	3,844.0	97,748.3	58,649.0	24,437.1	9,774.8	4,887.4
Class 5	74,015.5	44,409.3	18,503.9	7,401.6	4,626.0	103,093.1	61,855.8	25,773.3	10,309.3	5,154.7

Land Conversion (%)	Switchgrass Supply (t/year) 100	60	25	10	5	Miscanthus Supply (t/year) 100	60	25	10	5
Hamilton										
Class 1	112,472.2	67,483.3	28,118.0	11,247.2	5,623.6	178,991.4	107,394.8	44,747.8	17,899.1	8,949.6
Class 2	93,608.0	56,164.8	23,402.0	9,360.8	4,680.4	148,970.4	89,382.3	37,242.6	14,897.0	7,448.5
Class 3	183,072.0	109,843.2	45,768.0	18,307.2	9,153.6	262,316.1	157,389.6	65,579.0	26,231.6	13,115.8
Class 4	85,759.4	51,455.6	21,439.9	8,575.9	4,764.4	121,152.2	72,691.3	30,288.0	12,115.2	6,057.6
Class 5	44,624.4	26,774.6	11,156.1	4,462.4	2,789.0	62,155.4	37,293.3	15,538.9	6,215.5	3,107.8
Lambton										
Class 1	464,938.1	278,962.8	116,234.5	46,493.8	23,246.9	739,915.7	443,949.4	184,978.9	73,991.6	36,995.8
Class 2	1,137,352.5	682,411.5	284,338.1	113,735.3	56,867.6	1,810,015.3	1,086,009.2	452,503.8	181,001.5	90,500.8
Class 3	225,806.0	135,483.6	56,451.5	22,580.6	11,290.3	323,547.7	194,128.6	80,886.9	32,354.8	16,177.4
Class 4	738.0	442.8	184.5	73.8	41.0	1,042.6	625.5	260.6	104.3	52.1
Class 5	91,247.2	54,748.3	22,811.8	9,124.7	5,703.0	127,094.4	76,256.6	31,773.6	12,709.4	6,354.7
Middlesex										
Class 1	313,808.2	188,284.9	78,452.1	31,380.8	15,690.4	499,403.4	299,642.0	124,850.9	49,940.3	24,970.2
Class 2	1,082,140.5	649,284.3	270,535.1	108,214.1	54,107.0	1,722,149.4	1,033,289.6	430,537.3	172,214.9	86,107.5
Class 3	475,361.0	285,216.6	118,840.3	47,536.1	23,768.1	681,124.4	408,674.7	170,281.1	68,112.4	34,056.2
Class 4	22,117.4	13,270.4	5,529.3	2,211.7	1,228.7	31,245.2	18,747.1	7,811.3	3,124.5	1,562.3
Class 5	4,217.5	2,530.5	1,054.4	421.8	263.6	5,874.4	3,524.6	1,468.6	587.4	293.7
Niagara										
Class 1	36,777.0	22,066.2	9,194.3	3,677.7	1,838.9	58,528.0	35,116.8	14,632.0	5,852.8	2,926.4
Class 2	224,638.1	134,782.9	56,159.5	22,463.8	11,231.9	357,495.5	214,497.3	89,373.9	35,749.6	17,874.8
Class 3	642,546.2	385,527.7	160,636.5	64,254.6	32,127.3	920,676.9	552,406.1	230,169.2	92,067.7	46,033.8
Class 4	36,876.9	22,126.1	9,219.2	3,687.7	2,048.7	52,095.9	31,257.6	13,024.0	5,209.6	2,604.8
Class 5	43,074.6	25,844.7	10,768.6	4,307.5	2,692.2	59,996.7	35,998.0	14,999.2	5,999.7	2,999.8
Oxford										
Class 1	387,265.1	232,359.1	96,816.3	38,726.5	19,363.3	616,304.7	369,782.8	154,076.2	61,630.5	30,815.2
Class 2	827,003.2	496,201.9	206,750.8	82,700.3	41,350.2	1,316,116.6	789,669.9	329,029.1	131,611.7	65,805.8
Class 3	68,840.4	41,304.2	17,210.1	6,884.0	3,442.0	98,638.4	59,183.1	24,659.6	9,863.8	4,931.9
Class 4	12,255.3	7,353.2	3,063.8	1,225.5	680.8	17,313.0	10,387.8	4,328.3	1,731.3	865.7
Class 5	21,542.1	12,925.3	5,385.5	2,154.2	1,346.4	30,005.1	18,003.1	7,501.3	3,000.5	1,500.3

Land Conversion (%)	Switchgrass Supply (t/year)					Miscanthus Supply (t/year)				
	100	60	25	10	5	100	60	25	10	5
Bruce										
Class 1	830,304.8	498,182.9	207,576.2	83,030.5	41,515.2	1,321,370.8	792,822.5	330,342.7	132,137.1	66,068.5
Class 2	518,859.4	311,315.7	129,714.9	51,885.9	25,943.0	825,727.7	495,436.6	206,431.9	82,572.8	41,286.4
Class 3	199,717.6	119,830.6	49,929.4	19,971.8	9,985.9	286,166.9	171,700.1	71,541.7	28,616.7	14,308.3
Class 4	22,583.2	13,549.9	5,645.8	2,258.3	1,129.2	31,903.3	19,142.0	7,975.8	3,190.3	1,595.2
Class 5	262,011.3	157,206.8	65,502.8	26,201.1	13,100.6	364,944.3	218,966.6	91,236.1	36,494.4	18,247.2
Dufferin										
Class 1	356,642.9	213,985.7	89,160.7	35,664.3	17,832.1	567,571.6	340,543.0	141,892.9	56,757.2	28,378.6
Class 2	200,779.0	120,467.4	50,194.7	20,077.9	10,038.9	319,525.4	191,715.2	79,881.3	31,952.5	15,976.3
Class 3	118,549.0	71,129.4	29,637.3	11,854.9	5,927.5	169,863.8	101,918.3	42,466.0	16,986.4	8,493.2
Class 4	37,719.9	22,631.9	9,430.0	3,772.0	1,886.0	53,286.9	31,972.1	13,321.7	5,328.7	2,664.3
Class 5	33,315.3	19,989.2	8,328.8	3,331.5	1,665.8	46,403.4	27,842.0	11,600.8	4,640.3	2,320.2
Grey										
Class 1	838,431.5	503,058.9	209,607.9	83,843.2	41,921.6	1,334,303.9	800,582.3	333,576.0	133,430.4	66,715.2
Class 2	219,205.4	131,523.2	54,801.3	21,920.5	10,960.3	348,849.7	209,309.8	87,212.4	34,885.0	17,442.5
Class 3	557,634.9	334,580.9	139,408.7	55,763.5	27,881.7	799,011.1	479,406.7	199,752.8	79,901.1	39,950.6
Class 4	218,808.7	131,285.2	54,702.2	21,880.9	10,940.4	309,110.7	185,466.4	77,277.7	30,911.1	15,455.5
Class 5	504,815.6	302,889.3	126,203.9	50,481.6	25,240.8	703,135.9	421,881.6	175,784.0	70,313.6	35,156.8
Halton										
Class 1	164,365.9	98,619.5	41,091.5	16,436.6	8,218.3	261,576.6	156,946.0	65,394.1	26,157.7	13,078.8
Class 2	34,396.0	20,637.6	8,599.0	3,439.6	1,719.8	54,738.8	32,843.3	13,684.7	5,473.9	2,736.9
Class 3	152,833.7	91,700.2	38,208.4	15,283.4	7,641.7	218,988.9	131,393.3	54,747.2	21,898.9	10,949.4
Class 4	62,773.6	37,664.2	15,693.4	6,277.4	3,138.7	88,680.1	53,208.1	22,170.0	8,868.0	4,434.0
Class 5	25,877.0	15,526.2	6,469.3	2,587.7	1,293.9	36,043.0	21,625.8	9,010.7	3,604.3	1,802.1
Huron										
Class 1	1,160,078.3	696,047.0	290,019.6	116,007.8	58,003.9	1,846,181.7	1,107,709.0	461,545.4	184,618.2	92,309.1
Class 2	546,746.7	328,048.0	136,686.7	54,674.7	27,337.3	870,108.4	522,065.0	217,527.1	87,010.8	43,505.4
Class 3	258,042.8	154,825.7	64,510.7	25,804.3	12,902.1	369,738.4	221,843.1	92,434.6	36,973.8	18,486.9
Class 4	50,125.3	30,075.2	12,531.3	5,012.5	2,506.3	70,811.9	42,487.2	17,703.0	7,081.2	3,540.6
Class 5	132,580.2	79,548.1	33,145.0	13,258.0	6,629.0	184,665.2	110,799.1	46,166.3	18,466.5	9,233.3

Land Conversion (%)	Switchgrass Supply (t/year) 100	60	25	10	5	Miscanthus Supply (t/year) 100	60	25	10	5
Peel										
Class 1	226,306.9	135,784.1	56,576.7	22,630.7	11,315.3	360,151.2	216,090.7	90,037.8	36,015.1	18,007.6
Class 2	79,896.5	47,937.9	19,974.1	7,989.6	3,994.8	127,149.6	76,289.7	31,787.4	12,715.0	6,357.5
Class 3	80,886.5	48,531.9	20,221.6	8,088.6	4,044.3	115,898.8	69,539.3	28,974.7	11,589.9	5,794.9
Class 4	35,835.1	21,501.1	8,958.8	3,583.5	1,791.8	50,624.2	30,374.5	12,656.1	5,062.4	2,531.2
Class 5	41,018.5	24,611.1	10,254.6	4,101.9	2,050.9	57,132.9	34,279.8	14,283.2	5,713.3	2,856.6
Perth										
Class 1	1,035,835.4	621,501.2	258,958.8	103,583.5	51,791.8	1,648,458.0	989,074.8	412,114.5	164,845.8	82,422.9
Class 2	196,870.6	118,122.4	49,217.6	19,687.1	9,843.5	313,305.5	187,983.3	78,326.4	31,330.5	15,665.3
Class 3	146,577.8	87,946.7	36,644.4	14,657.8	7,328.9	210,025.0	126,015.0	52,506.2	21,002.5	10,501.2
Class 4	4,581.7	2,749.0	1,145.4	458.2	229.1	6,472.6	3,883.6	1,618.1	647.3	323.6
Class 5	52,536.0	31,521.6	13,134.0	5,253.6	2,626.8	73,175.1	43,905.1	18,293.8	7,317.5	3,658.8
Simcoe										
Class 1	566,908.4	340,145.1	141,727.1	56,690.8	28,345.4	902,194.3	541,316.6	225,548.6	90,219.4	45,109.7
Class 2	507,798.7	304,679.2	126,949.7	50,779.9	25,389.9	808,125.4	484,875.2	202,031.3	80,812.5	40,406.3
Class 3	628,028.6	376,817.1	157,007.1	62,802.9	31,401.4	899,875.2	539,925.1	224,968.8	89,987.5	44,993.8
Class 4	320,048.1	192,028.9	80,012.0	32,004.8	16,002.4	452,131.4	271,278.9	113,032.9	45,213.1	22,606.6
Class 5	128,219.5	76,931.7	32,054.9	12,822.0	6,411.0	178,591.5	107,154.9	44,647.9	17,859.1	8,929.6
Waterloo										
Class 1	251,753.5	151,052.1	62,938.4	25,175.3	12,587.7	400,647.7	240,388.6	100,161.9	40,064.8	20,032.4
Class 2	298,365.9	179,019.5	74,591.5	29,836.6	14,918.3	474,828.0	284,896.8	118,707.0	47,482.8	23,741.4
Class 3	98,706.6	59,224.0	24,676.7	9,870.7	4,935.3	141,432.5	84,859.5	35,358.1	14,143.2	7,071.6
Class 4	71,399.4	42,839.6	17,849.8	7,139.9	3,570.0	100,865.8	60,519.5	25,216.4	10,086.6	5,043.3
Class 5	14,179.5	8,507.7	3,544.9	1,417.9	709.0	19,750.0	11,850.0	4,937.5	1,975.0	987.5
Wellington										
Class 1	950,348.3	570,209.0	237,587.1	95,034.8	47,517.4	1,512,411.5	907,446.9	378,102.9	151,241.1	75,620.6
Class 2	201,757.0	121,054.2	50,439.2	20,175.7	10,087.8	321,081.8	192,649.1	80,270.4	32,108.2	16,054.1
Class 3	280,576.4	168,345.8	70,144.1	28,057.6	14,028.8	402,025.8	241,215.5	100,506.5	40,202.6	20,101.3
Class 4	47,089.7	28,253.8	11,772.4	4,709.0	2,354.5	66,523.5	39,914.1	16,630.9	6,652.3	3,326.2
Class 5	122,798.8	73,679.3	30,699.7	12,279.9	6,139.9	171,041.1	102,624.7	42,760.3	17,104.1	8,552.1

Land Conversion (%)	Switchgrass Supply (t/year) 100	60	25	10	5	Miscanthus Supply (t/year) 100	60	25	10	5
Durham										
Class 1	620,022.4	372,013.5	155,005.6	37,201.3	18,600.7	986,721.4	592,032.8	246,680.4	59,203.3	29,601.6
Class 2	298,192.6	178,915.6	74,548.2	17,891.6	8,945.8	474,552.2	284,731.3	118,638.1	28,473.1	14,236.6
Class 3	167,195.4	100,317.3	41,798.9	10,031.7	5,015.9	239,567.2	143,740.3	59,891.8	14,374.0	7,187.0
Class 4	134,552.3	80,731.4	33,638.1	8,073.1	4,036.6	190,081.8	114,049.1	47,520.4	11,404.9	5,702.5
Class 5	93,430.2	56,058.1	23,357.6	5,605.8	2,802.9	130,134.9	78,081.0	32,533.7	7,808.1	3,904.0
Hastings										
Class 1	229,364.6	137,618.7	57,341.1	13,761.9	6,880.9	365,017.3	219,010.4	91,254.3	21,901.0	10,950.5
Class 2	80,276.6	48,165.9	20,069.1	4,816.6	2,408.3	127,754.4	76,652.6	31,938.6	7,665.3	3,832.6
Class 3	450,789.1	270,473.4	112,697.3	27,047.3	13,523.7	645,916.4	387,549.8	161,479.1	38,755.0	19,377.5
Class 4	138,311.6	82,987.0	34,577.9	8,298.7	4,149.3	195,392.6	117,235.6	48,848.2	11,723.6	5,861.8
Class 5	241,381.6	144,829.0	60,345.4	14,482.9	7,241.4	336,210.1	201,726.1	84,052.5	20,172.6	10,086.3
Kawartha										
Class 1	453,537.1	272,122.2	113,384.3	27,212.2	13,606.1	721,771.8	433,063.1	180,443.0	43,306.3	21,653.2
Class 2	144,609.9	86,765.9	36,152.5	8,676.6	4,338.3	230,136.2	138,081.7	57,534.1	13,808.2	6,904.1
Class 3	45,874.4	27,524.7	11,468.6	2,752.5	1,376.2	65,731.5	39,438.9	16,432.9	3,943.9	1,971.9
Class 4	289,400.0	173,640.0	72,350.0	17,364.0	8,682.0	408,835.0	245,301.0	102,208.7	24,530.1	12,265.0
Class 5	82,656.6	49,593.9	20,664.1	4,959.4	2,479.7	115,128.8	69,077.3	28,782.2	6,907.7	3,453.9
Northumberland										
Class 1	143,933.4	86,360.0	35,983.3	8,636.0	4,318.0	229,059.7	137,435.8	57,264.9	13,743.6	6,871.8
Class 2	168,044.5	100,826.7	42,011.1	10,082.7	5,041.3	267,430.8	160,458.5	66,857.7	16,045.8	8,022.9
Class 3	285,364.2	171,218.5	71,341.0	17,121.9	8,560.9	408,886.1	245,331.7	102,221.5	24,533.2	12,266.6
Class 4	203,410.2	122,046.1	50,852.6	12,204.6	6,102.3	287,357.3	172,414.4	71,839.3	17,241.4	8,620.7
Class 5	113,059.6	67,835.8	28,264.9	6,783.6	3,391.8	157,475.9	94,485.5	39,369.0	9,448.6	4,724.3
Peterborough										
Class 1	90,835.7	54,501.4	22,708.9	5,450.1	2,725.1	144,558.6	86,735.1	36,139.6	8,673.5	4,336.8
Class 2	89,457.6	53,674.5	22,364.4	5,367.5	2,683.7	142,365.3	85,419.2	35,591.3	8,541.9	4,271.0
Class 3	326,729.2	196,037.5	81,682.3	19,603.8	9,801.9	468,156.3	280,893.8	117,039.1	28,089.4	14,044.7
Class 4	303,560.6	182,136.3	75,890.1	18,213.6	9,106.8	428,839.6	257,303.7	107,209.9	25,730.4	12,865.2
Class 5	150,420.8	90,252.5	37,605.2	9,025.2	4,512.6	209,514.6	125,708.8	52,378.7	12,570.9	6,285.4

Land Conversion (%)	Switchgrass Supply (t/year) 100	60	25	10	5	Miscanthus Supply (t/year) 100	60	25	10	5
Prince Edward										
Class 1	150,866.2	90,519.7	37,716.6	9,052.0	4,526.0	240,092.8	144,055.7	60,023.2	14,405.6	7,202.8
Class 2	266,054.3	159,632.6	66,513.6	15,963.3	7,981.6	423,406.4	254,043.9	105,851.6	25,404.4	12,702.2
Class 3	32,463.2	19,477.9	8,115.8	1,947.8	973.9	46,515.1	27,909.1	11,628.8	2,790.9	1,395.5
Class 4	4,294.9	2,577.0	1,073.7	257.7	128.8	6,067.4	3,640.5	1,516.9	364.0	182.0
Class 5	30,726.9	18,436.1	7,681.7	1,843.6	921.8	42,798.1	25,678.9	10,699.5	2,567.9	1,283.9
York										
Class 1	396,015.2	237,609.1	99,003.8	23,760.9	11,880.5	630,229.9	378,137.9	157,557.5	37,813.8	18,906.9
Class 2	188,317.0	112,990.2	47,079.2	11,299.0	5,649.5	299,693.0	179,815.8	74,923.2	17,981.6	8,990.8
Class 3	89,887.8	53,932.7	22,472.0	5,393.3	2,696.6	128,796.4	77,277.8	32,199.1	7,727.8	3,863.9
Class 4	102,351.8	61,411.1	25,588.0	6,141.1	3,070.6	144,592.3	86,755.4	36,148.1	8,675.5	4,337.8
Class 5	89,179.3	53,507.6	22,294.8	5,350.8	2,675.4	124,214.1	74,528.4	31,053.5	7,452.8	3,726.4

Land Conversion (%)	Switchgrass Supply (t/year) 100	60	25	10	5	Miscanthus Supply (t/year) 100	60	25	10	5
Frontenac										
Class 1	50,189.4	30,113.6	12,547.3	5,018.9	2,509.5	79,872.8	47,923.7	19,968.2	7,987.3	3,993.6
Class 2	156,702.9	94,021.8	39,175.7	15,670.3	7,835.1	249,381.6	149,628.9	62,345.4	24,938.2	12,469.1
Class 3	102,804.4	61,682.6	25,701.1	10,280.4	5,140.2	147,304.0	88,382.4	36,826.0	14,730.4	7,365.2
Class 4	88,912.2	53,347.3	22,228.1	8,891.2	4,445.6	125,606.1	75,363.7	31,401.5	12,560.6	6,280.3
Class 5	139,534.0	83,720.4	34,883.5	13,953.4	6,976.7	194,350.9	116,610.5	48,587.7	19,435.1	9,717.5
Lanark										
Class 1	31,884.7	19,130.8	7,971.2	3,188.5	1,594.2	50,742.3	30,445.4	12,685.6	5,074.2	2,537.1
Class 2	210,949.5	126,569.7	52,737.4	21,094.9	10,547.5	335,711.0	201,426.6	83,927.8	33,571.1	16,785.6
Class 3	85,073.3	51,044.0	21,268.3	8,507.3	4,253.7	121,897.8	73,138.7	30,474.5	12,189.8	6,094.9
Class 4	79,621.7	47,773.0	19,905.4	7,962.2	3,981.1	112,481.4	67,488.8	28,120.4	11,248.1	5,624.1
Class 5	19,704.7	11,822.8	4,926.2	1,970.5	985.2	27,445.9	16,467.5	6,861.5	2,744.6	1,372.3
Leeds & Grenville										
Class 1	1,872.0	1,123.2	468.0	187.2	93.6	2,979.1	1,787.4	744.8	297.9	149.0
Class 2	425,179.0	255,107.4	106,294.7	42,517.9	21,258.9	676,641.9	405,985.2	169,160.5	67,664.2	33,832.1
Class 3	262,782.9	157,669.8	65,695.7	26,278.3	13,139.1	376,530.4	225,918.2	94,132.6	37,653.0	18,826.5
Class 4	152,092.5	91,255.5	38,023.1	15,209.3	7,604.6	214,860.8	128,916.5	53,715.2	21,486.1	10,743.0
Class 5	131,754.5	79,052.7	32,938.6	13,175.5	6,587.7	183,515.2	110,109.1	45,878.8	18,351.5	9,175.8
Lennox & Addington										
Class 1	92,335.7	55,401.4	23,083.9	9,233.6	4,616.8	146,945.7	88,167.4	36,736.4	14,694.6	7,347.3
Class 2	76,312.5	45,787.5	19,078.1	7,631.3	3,815.6	121,446.0	72,867.6	30,361.5	12,144.6	6,072.3
Class 3	209,141.5	125,484.9	52,285.4	20,914.2	10,457.1	299,669.9	179,801.9	74,917.5	29,967.0	14,983.5
Class 4	60,907.2	36,544.3	15,226.8	6,090.7	3,045.4	86,043.4	51,626.1	21,510.9	8,604.3	4,302.2
Class 5	51,622.1	30,973.3	12,905.5	5,162.2	2,581.1	71,902.2	43,141.3	17,975.6	7,190.2	3,595.1
Prescott & Russell										
Class 1	2,906.8	1,744.1	726.7	290.7	145.3	4,626.0	2,775.6	1,156.5	462.6	231.3
Class 2	314,959.4	188,975.6	78,739.9	31,495.9	15,748.0	501,235.4	300,741.2	125,308.9	50,123.5	25,061.8
Class 3	496,102.9	297,661.8	124,025.7	49,610.3	24,805.1	710,844.6	426,506.8	177,711.2	71,084.5	35,542.2
Class 4	291,142.8	174,685.7	72,785.7	29,114.3	14,557.1	411,297.0	246,778.2	102,824.2	41,129.7	20,564.8
Class 5	63,793.5	38,276.1	15,948.4	6,379.3	3,189.7	88,855.2	53,313.1	22,213.8	8,885.5	4,442.8

Land Conversion (%)	Switchgrass Supply (t/year) 100	60	25	10	5	Miscanthus Supply (t/year) 100	60	25	10	5
Renfrew										
Class 1	9,066.5	5,439.9	2,266.6	906.6	453.3	14,428.7	8,657.2	3,607.2	1,442.9	721.4
Class 2	117,478.0	70,486.8	29,369.5	11,747.8	5,873.9	186,957.8	112,174.7	46,739.5	18,695.8	9,347.9
Class 3	689,107.2	413,464.3	172,276.8	68,910.7	34,455.4	987,392.1	592,435.3	246,848.0	98,739.2	49,369.6
Class 4	748,018.9	448,811.3	187,004.7	74,801.9	37,400.9	1,056,725.1	634,035.1	264,181.3	105,672.5	52,836.3
Class 5	46,993.4	28,196.0	11,748.4	4,699.3	2,349.7	65,455.1	39,273.1	16,363.8	6,545.5	3,272.8
Stormont, Dundas										
Class 1	26,132.5	15,679.5	6,533.1	2,613.3	1,306.6	41,588.1	24,952.8	10,397.0	4,158.8	2,079.4
Class 2	1,217,436.1	730,461.7	304,359.0	121,743.6	60,871.8	1,937,462.7	1,162,477.6	484,365.7	193,746.3	96,873.1
Class 3	475,222.7	285,133.6	118,805.7	47,522.3	23,761.1	680,926.2	408,555.7	170,231.5	68,092.6	34,046.3
Class 4	129,841.7	77,905.0	32,460.4	12,984.2	6,492.1	183,427.2	110,056.3	45,856.8	18,342.7	9,171.4
Class 5	132,158.6	79,295.1	33,039.6	13,215.9	6,607.9	184,078.0	110,446.8	46,019.5	18,407.8	9,203.9