Report on Literature Review of Agronomic Practices for Energy Crop Production under Ontario Conditions

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Acronyms & Abbreviations

Al: Aluminum

C: Carbon

C3 Plant: Carbon 3-Plant (CO_2 is first incorporated into a 3-carbon compound in the photosynthetic process.

C4 Plant: Carbon 4-Plant (CO_2 is first incorporated into a 4-carbon compound in the photosynthetic process.

Ca: Calcium

CO_2: Carbon dioxide

CHP: Combined Heat & Power

CHU: Crop Heat Units

Cl: Chlorine

CLI: Canada Land Inventory

CRP: Conservation Reserve Program

Cu: Copper

CV: Calorific Value

Fe: Iron

ha: hectares

HAG: Herbaceous Annual Grasses

HBS: High Biomass Sorghum

HHV: Higher Heating Value

HPG: Herbaceous Perennial Grasses

ISO: International Organization for Standards

K: Potassium

LCA: Life Cycle Analysis

LHV: Lower Heating Value

Mg: Magnesium

N: Nitrogen

Na: Sodium

OMAFRA: Ontario Ministry of Agriculture, Food and Rural Affairs

P: Phosphorus

PCA: Process Chain Analysis

PDI: Pellet Durability Index

PCDD: Polychlorinated dibenzo-p-dioxin

PCDF: Polychlorinated dibenzofuran

PLS: Pure Live Seed

SRC: Short Rotation Coppices

Si: Silicon

SOC: Soil Organic Carbon

SOM: Soil Organic Matter

tDM: tonnes of Dry Matter

Contents

Executive Summary

This report provides a global literature review of the agronomic practices and technologies used today to produce some selected energy crops for the purpose of developing a sustainable energy crop industry in Ontario. The agronomics of each crop, the technical challenges, limitations and risks to commercial production of the energy crops, anticipated environmental impacts of producing energy crops, and legal issues associated with accessing biomass plant source materials are the major issues reviewed in this study. A selection matrix is developed to help in selecting energy crops suitable for a particular location with specific conditions and resources. The study also highlights major biomass densification and processing technologies currently adopted world-wide, and provides estimates of energy crop supply in Ontario based on land classes and their biomass yield potential. The report provides suggestions of the areas that require further research work in developing the biomass fuel program in Ontario.

Miscanthus *(Miscanthus spps.)*, switchgrass *(Panicum virgatum)*, reed canarygrass *(Phalaris arundacea)*, high-biomass sorghum *(Sorghum spp.)* and poplar *(Poplar spp.)* are the energy crops being considered for the biomass industry in Ontario. Our research findings indicate that each of these crops requires specific soil and climatic conditions and management practices for their sustainable production and that crop selection for an area should be based on their specific characteristics. For example, whereas some crops are adapted to a wide range of soil and climatic conditions (e.g. reed canarygrass), others have limited capabilities in this regard (e.g. Miscanthus). For some species, winter survival is the major challenge especially during establishment (e.g. switchgrass) while some are very susceptible to multiple insect pests and diseases (e.g. high-biomass sorghum and poplar). Harvest time influences the yield, moisture and composition of the biomass. Although delayed harvesting improves the combustion qualities in some, this practice does not help in others (e.g. reed canarygrass). A mixed-crop scheme, where a mixture of crops is planted in an area instead of monoculture, has been identified as a practical strategy to ensure uninterrupted supply of biomass. For both Miscanthus and switchgrass, no major peats and diseases have been identified that would have a significant impact on their production and yield.

Recycling of ash to agricultural and forest land could return nutrients to the soil and could contribute to the sustainable use of biomass for power generation. Although this practice is already being implemented to some extent in some European countries such as Sweden, Finland, Austria and Germany, it is currently non-existent in Canada. Several factors could affect the ash quality of herbaceous biomass, namely (1) plant type and species, (2) plant fractions growing conditions, (3) harvest time, (4) handling and storage, and (5) pre-processing. Of these factors, the manipulation of harvest time (e.g. delayed harvesting) that results in field leaching of undesirable chemical elements in biomass is being seriously promoted in North America, including Ontario. However, delayed harvest alone does not guarantee quality standards; delayed harvest can also have important tradeoffs, such as a high loss of plant matter (which reduces yields considerably) or an increase in total ash (due to losses of organic matter). Research into alternative pre-processing techniques to leach out inorganic constituents from biomass without sacrificing biomass yields and/or quality is therefore warranted.

Biomass densification serves to increase both the energy density and the bulk density of biomass; **a lower energy content implies more biofuel is required to obtain the same amount of energy and also a larger space for storage and higher costs for transportation to processing sites because of the lower bulk density.** Our review indicates that mechanical densification products such as *bales, pellets, briquettes, pucks and cubes* are applicable to the Ontario condition. Apart from bales, pellets are the only known established densified product in Ontario. There is however little or no information on the biomass types suited to each of these products; research in this area is therefore highly recommended. Torrefaction can be used to improve the properties of biomass in relation to thermochemical processing techniques for energy generation. A major advantage of torrefaction is that it can convert biomass feedstocks which have non-uniform qualities into more uniform materials. However, torrefaction does not address the issues related to biomass chemical properties such as ash content and chemical composition that negatively affect the performance of combustion processes and costs. The review also identified farm-level management practices that may be used to improve biomass quality for better combustion; such practices/strategies include crop selection, modifying growing conditions, plant fractionation during harvesting, manipulation of harvesting time and minimizing soil contamination.

Process-chain-analysis (PCA*), carbon footprint, water footprint, energy balances, carbon offset generation, soil erosion, phytoremediation and biodiversity* **are examples of potentially significant environmental issues that may impact energy crop production**. The quantification and discussion of these environmental issues for each energy crop is however beyond the scope of this study. Furthermore, the literature lacks all the necessary data and analyses required. A full assessment of each of the environmental issues requires a comprehensive life cycle analysis (LCA). There is therefore an urgent need to initiate LCA studies on each and every potential energy crop to provide systematic inventory and impact assessment of the environmental implications throughout its life cycle

The principal aim of improving and selecting planting materials is to boost biomass yields, to improve resistance to both biotic and abiotic stresses and to enhance the feedstock quality for producing power and electricity. A key to the appropriate selection of energy lies with the planting materials to use. The technical development, sourcing and use of bioenergy crop planting materials however entail legal and propriety issues related to intellectual property rights, seed technology patents, licensing agreements, contracts and royalties. For example, ***"the Ceres Seed Use Agreement"*** binds the seed purchaser with the terms and conditions in the Agreement. Currently, Miscanthus rhizomes procured from ***New Energy Farms*** have no onward royalties and have unencumbered use; similarly, switchgrass seeds purchased from ***Ernst Seed Company*** can be planted and the seeds saved for use in subsequent years. However, as new energy planting materials are developed through advances in biotechnology, new legal issues will emerge regarding the use of such biotech materials, and non-compliance of the laws could adversely impact both biomass producers and biomass end-users. To avoid any infringement, all stakeholders would have to develop a workable approach to keep abreast with newly developed planting materials and processes.

Based on available tillable land and productivity of the land classes under Ontario conditions, Ontario is capable of producing millions of tonnes of energy crop biomass annually. In this study, it is assumed there is no restriction on the conversion of any land class (Classes 1-5 lands) to energy crop production, and that the proportions of land classes that would be allocated to production would be dictated by economic considerations. It is also assumed that biomass productivity (yield/land area) on *"high-valued lands"* (Classes 1, 2 and 3 lands) is higher than that on "*marginal lands" (Classes 4 and 5 lands).* The amount of an energy crop biomass that can be potentially produced from each land class is obtained by multiplying the tillable land area in each of the five regions of Ontario by the corresponding average productivity of an energy crop. Our analysis indicates that even if only 5% of land classes is used to produce Miscanthus across Ontario, we could obtain 2.5 million tDM biomass annually, assuming there is 100% recovery during harvesting; if the biomass originates from switchgrass, about 1.5 million tons dry matter (tDM) would be obtained. The amounts for reed canarygrass, high-biomass sorghum and poplar are 1.9, 2.3 and 2.9 million tDM, respectively. Mixed-crop scenarios involving the use of our 5 selected energy crops grown in combinations on only portions of tillable land across Ontario could produce substantial amounts of biomass.

In conclusion, Ontario is making significant progress in acquiring necessary information on successful cultivation of switchgrass, Miscanthus and Poplar, but lacks detailed information on the agronomics of reed canarygrass and high-biomass sorghum. Other promising energy crops such as Giant Reed (*Arundo donax L),* Hemp *(Cannabis sativa) and* Jerusalem artichoke *(Helianthus tuberosus* L) should be considered in future studies. **Large-scale production of these crops in Ontario would require more strategic research, transparent government energy policies, demonstration farms, and establishment of densification technologies across the province.** Full life-cycle analysis of generating heat and electricity from these energy crops should however be a prerequisite to their adoption; such a study would provide valuable economic and environmental feasibility assessment of using these crops for power and electricity generation in Ontario. Research into alternative pre-processing techniques to leach out inorganic constituents from biomass without sacrificing biomass yields and/or quality is also warranted.

Chapter 1 Characteristics and Description of Biomass Crops

Biomass crops are a group of plant species that are purposely grown to provide biomass from which some form of energy is produced. The suitability of a biomass crop for a chosen area is determined by several factors particularly the technical or environmental suitability (e.g. climate, soil, and landscape topography), biomass yields, environmental impact, and costs and returns involved in its production. For the thermochemical conversion platform, the ideal attributes of a biomass crop include high yield potential, high lignin and cellulose contents, positive environmental impact, ability to recycle and store nutrients, and low requirements for fertilizers and agrochemicals. In addition, the end-use criteria of the biomass crop species should include its moisture content at harvest, the calorific/energy content, the chemical composition of harvested biomass, and the ash content and properties of the harvested biomass.

Biomass crops are generally grouped into either herbaceous or woody species. Herbaceous species are mostly perennial grasses (HPG) and include plants such as Miscanthus *(Miscanthus spps.)*, switchgrass (*Panicum virgatum)*, big blue stem (*Andropogon gerardii)*, reed canarygrass (*(Phalaris arundinacea)*, prairie cord grass (*Spartina pectinata*), and common reed (*Phragmites australis*. These grasses are usually harvested on a yearly basis after establishment and need no replanting for at least 10 years. Annual species such as high biomass sorghum (HAG) *(Sorghum spp.)* are also included in the herbaceous group. Woody biomass crops are short rotation coppices (SRC) and include species such as willow *(Salix spp.)* and poplar (*Populus spp.),* that are harvested on a 3-5 year cycle. After harvesting, the rootstock of SRC regrows to produce new shoots; for most SRC species, replanting is not necessary for at least 21 years.

This chapter reviews the agronomic and production requirements of five selected biomass species, namely four grass species (three perennials: Miscanthus, switchgrass, reed canarygrass, and one annual: high-biomass sorghum), and one woody biomass crop (poplar). Although the review is global in scope, attempts were made to compare and identify the requirements in the context of Ontario conditions. Our attempt is to provide farmers with relevant information on the production, management and processing of these crops and thereby shorten the learning curve in bioenergy feedstock supply in the province. For each biomass crop, we have provided information on the following agronomic issues: origin and global distribution**,** type of plant**,** propagation and varieties/germplasm for biomass production, soil and climatic conditions suitable for the crop, optimal planting dates/times, establishment, fertilization and weed management, pest and disease control, optimal times and methods to harvest, ways and methods to store the harvested biomass, yield potential, alternative uses of biomass, and technical challenges, and limitations and risks to commercial production of the crop. At the end of the chapter, we summarized our results into a selection matrix that would enable the prospective grower select the crops that would perform best in his/her particular location. The costs and revenue involved in the production and processing of the crops are however not included in this review.

1. Miscanthus (*Miscanthus spp*.)

Type of Plant

Miscanthus is a perennial, warm-season rhizomatous grass that can grow at relatively low temperatures. Miscanthus utilizes the *C4 photosynthetic pathway* (C4 plants have relatively high photosynthetic efficiencies compared to plants that utilize other pathways; common examples of C4 plants include corn, sugarcane and pineapple). Miscanthus is unique among C4 species that are typically susceptible to damage at cold temperatures because it retains high photosynthetic activity at low temperatures and remains highly productive in cold climates (Lewandowski et al., 2000; Linde-Lausen 1993; Beale et al., 1996; Naidu et al., 2003). Notably, *M.* × *giganteus* is able to develop photosynthetically active leaves at temperatures as low as 8°C (Naidu et al. 2003). 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 relatively low nutrient requirement, noninvasiveness, good water use efficiency, rapid growth (up to over 3.5 m in one growing season), promising annual yield, relatively 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 to produce heat and electricity. 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. 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 on the continent 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.

Origins and global distribution

Miscanthus species are native to Southeastern Asia, China, Japan, Polynesia and Africa, and are currently distributed throughout temperate and tropical areas of the world (Hodkinson and Jones, 2001). Miscanthus was first cultivated in Europe in the 1930s, as an ornamental introduction from Japan. Owing to its high productivity across a variety of conditions, *M.* x *giganteus* has been grown successfully from the Mediterranean climates of Spain to as far north as Scandinavia (Carroll 2009). The yield potential of miscanthus for cellulose fiber production was investigated in the late 1960s in Denmark. Trials for bioenergy production commenced in Denmark in 1983 and spread to Germany in 1987 before more widespread evaluation throughout Europe (Scurlock, 1999).

Varieties/germplasm for biomass production

The genus *Miscanthus* comprises a group of more than 15 perennial grass species. Miscanthus *sinensis* (diploid, 2n=38) and Miscanthus *sacchariflorus* (tetraploid, 4n=76) are parents of Miscanthus x *giganteus* which is a sterile triploid (3n=57), and has been at the centre of extensive research and field trials in Europe and North America. Cultivars of *M. sacchariflorus, M. sinensis,* their hybrids, and other Miscanthus species are grown in North America as ornamental crops. 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). Several research trials reported *M. x giganteus* was the most productive of all the genotypes tested (Scurlock, 1998; Clifton-Brown et al., 2001). Once successfully established, Miscanthus seems to be tolerant of cold climate. The *M. x giganteus* stands at the University of Illinois survived winters with periods below -23°C without plant loss (Pyter et al., 2007). *Miscanthus x giganteus* is likely the right variety for southwestern Ontario, since it is being successfully grown with good yields in Illinois. Miscanthus cultivars being tested at the University of Guelph Research Station at Elora include *Nagara, Amori*, and *Polish*.

Soil and climatic conditions suitable for Miscanthus

The soil is an important factor for Miscanthus productivity. *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). Miscanthus yield on fertile soils can reach up to 30 tDM/ha/yr. However, the yield on less productive soils can hardly reach 10 tDM/ha/yr. Increases in productivity result in increases in water demand. For example, in order to produce maximum yields, *M x giganteus* is able to utilize large quantities of water, up to 900 mm/year. Biomass production is positively linked to seasonal precipitation and can decline considerably under water-stressed conditions. Miscanthus can be grown in the regions with total annual precipitation ranging from 600-1500 mm (Prince et al., 2003); therefore, water requirement for miscanthus should not be an issue for Ontario, where an annual rainfall is 900-1000 mm. Miscanthus also possesses good water use efficiency when considered on the basis of the amount of water required per unit of biomass, and Miscanthus roots can penetrate and extract water to a depth of around 2m. It may not however be adaptable in the northern region of Ontario because of the colder climate. In North America, *M. x giganteus* plantings have been established successfully in Ohio, Michigan, Indiana, Illinois, Quebec, and recently in southwestern Ontario. Stand failure has been reported for Wisconsin. Several conclusions can be made with regards to the soil preference of Miscanthus (Christian and Haase, 2001):

- Soil that is suitable for growing corn is also likely to be suitable for Miscanthus; however, yields decrease on marginal lands particularly in areas where soil moisture is low
- The most suitable soil for growing Miscanthus is a medium soil such as a *sandy or silty loam* with a good air movement, a high water-holding capacity and organic matter content;
- Maximum yields are not achieved when the crop is grown on shallow soils in combination with long dry spells during summer although establishment and survival are possible;
- Cold and heavy waterlogged soils (e.g. clays) are not suitable for growing Miscanthus (because of low tiller number and plant height);
- It is possible to grow Miscanthus in sandy soils with a low water capacity but yields are low in these circumstances;

Miscanthus field trials remain very limited in Ontario, but there has been improvement in this regard in recent years.

Optimal planting dates/times

Miscanthus has a growing season in Ontario that begins in spring (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 2m in height by the end of May and greater than 4m 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 Establishment

Miscanthus rhizome (Photo courtesy of Ceres, Inc)

Miscanthus is propagated vegetatively using roots or divided rhizomes (underground stems), 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). The use of *rhizome-derived plugs* to establish Miscanthus stands is gaining popularity in North America. This method involves planting small rhizome pieces into pots approximately 3 cm in diameter and 15cm deep under greenhouse or high-tunnel conditions until the rhizome pieces become well rooted and have developed adequate shoots to support in-field development. Following establishment, the plugs are transplanted into the field using mechanical transplanters similar to those used to plant nursery crops. ***Rhizome-derived plugs*** in Ontario are being developed by the ***New Energy Farms*** in Leamington. However, these actively growing plants are vulnerable to dry weather, and irrigation may have to be applied to ensure survival and establishment. Current methods of establishing Miscanthus stands in Ontario include the use of rhizomes, roots and rhizome-derived plugs.

Rhizome-derived plugs.

Currently the planting time in Western and Southern Ontario is mid April through May. The rhizomes are planted approximately 10cm deep at a spacing of 0.9m between rows and 0.9m within rows (approximately 11,984 rhizomes/ha or 4,000 rhizomes/ac) (Pyter et al., 2007). Existing planting equipment are being used for planting. For example, at the Mississippi State University research station, tobacco planters are being used until precision planters being developed become operational. 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). 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.

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 *M. 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). *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).

Once planted, survival of first-year *M.* x *giganteus* is highly dependent on the environment (Anderson et al., 2011). In addition to competition from weeds and pests, cold tolerance and over-winter survival of first-year stands is of much concern especially in temperate areas with cold winters and little snow cover. Clifton-Brown and Lewandowski (2000) and Clifton-Brown *et al.* (2001) examined first-year cold tolerance, and their results indicate a major risk to viability when soil temperatures drop below -3°C at the 5-cm soil level, with lethal rates of up to 50%.

In comparing Illinois seven test sites, Pyter et al. (2007) 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 Also, not all rhizomes will sprout requiring 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).

Post-establishment fertilization & weed management

Following establishment, Giant Miscanthus appears to be remarkably efficient at capturing and retaining nitrogen. Fertilizer application rates reported in the literature vary widely, and the effect of fertilization on *M.* x *giganteus* yields varies widely based on location, study type. Fertilizers are not needed in the first two years of establishment, but maintenance fertilizer rates are required in later years. 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. In European trials, there was no significant effect of nitrogen fertilization on yield (Lewandowski et al., 2000). For example, Christian *et al.* (2008) found no response to N fertilization at England's Rothamsted Research Farm (UK) after 14 years; yield reductions were not observed even at sites where no nitrogen had been applied. Similarly in West Germany, Himken *et al.* (1997) found no effects from N fertilization in a fourth-year planting. In Iowa in the US, annual nutrient removal by harvested Miscanthus was estimated as follows: N=16-20kg/tDM; P=3kg/tDM; K=16kg/tDM (Heaton et al., 2010). Table 1.1 lists the various rates of fertilization used in different studies. 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.

Table 1.1Fertilizer 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. *M.* x *giganteus* competes poorly with weeds during the establishment phase, thus making weed control highly essential (Christian and Haase, 2001; Lewandowski et al., 1995). Yields of herbaceous perennial species can be reduced by weed growth through resource competition (water, nutrients, light and space), and also through the production of *allelochemicals* (Buhler et al., 1998). Mechanical, cultural and chemical weed-management practices are all options at various points during the establishment period. Mechanical and cultural methods of weed control in *M.* x *giganteus* include the use of a rotary hoe between rows several times in the second year (Schwarz et al., 1994), cleaning rhizomes of loose soil before planting (Speller, 1993), cleaning tillage and planting equipment, timing planting to avoid emergence periods of problematic weeds, minimizing the weed-seed bank population through consistent weed control in prior years, and either banding fertilizer or foregoing fertilizer applications when planting and harvesting *M.* x *giganteus* only once each year at the recommended time (Buhler et al., 1998). After the second growing season, the canopy generally closes early in the season, reducing weed competition until the first killing frost (Anderson et al., 2011).

In North America, no herbicides are currently registered for use in the biofuel planting of Miscanthus. Labelled herbicide choices are currently limited in use for ornamental plantings of Miscanthus spp. In the European Union however, various pre-emergence and post-emergence herbicides have been used for weed control, and it is generally presumed that herbicides used in corn are safe on *M.* x *giganteus* (Lewandowski et al., 2000; Bullard et al., 1995). In North America, pre-emergence and post-emergence herbicide combinations safely applied to M x giganteus 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 ongoing.

Pest and disease control

Very few insect pests have been found to infest Miscanthus, and no reports of yield reductions have been cited. However, two key pests, the common rustic moth and the ghost moth larvae, have been seen feeding on Miscanthus and might cause future problems (DEFRA, 2007). Also, nematodes were detected in soils surrounding *M.* x *giganteus* roots at several sampling sites in Midwest USA (Mekete et al., 2009). High numbers of these nematodes appeared to destroy fibrous roots and stunt lateral roots. To date, there are no reports of plant diseases significantly limiting Miscanthus production. The crop is, however, known to be susceptible to *Fusarium* blight and Barley Yellow Dwarf Luteovirus that may present a significant risk (Walsh and McCarthy 1998). Currently, there are no registered pesticides for Miscanthus.

Optimal times to harvest, and ways and methods to harvest

Harvest of Miscanthus should be carried out after the crop has senesced, when the moisture content is lowest and before regrowth begins (usually at temperatures >10^{o}C). The moisture content at harvest is important in ensuring high quality biomass. Most 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 1.2). 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 1.2. The impact of delayed harvesting on the mineral and carbohydrate content of Miscanthus (Lewandowski et al. 2000)

Mineral content	Harvest date	
(% dry matter)	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

Miscanthus harvesting can be carried out using a number of different machines such as a mower conditioner, forage harvester, maize harvester with a specially adopted head (kemper) to cut the grass, balers to bale the product, and transport with conventional transportation. Miscanthus can also be harvested every year with a sugar cane harvester. The cutting part of the harvester should be adjusted at the lowest possible way to avoid yield losses. Some machines are especially adapted to cut/mow, chop, and bale in a single-phase procedure. In a multi-phase procedure, separate machines are used for cutting/mowing, swathing, compacting and baling. The bales may be round or square bales. Currently, harvesting technology for *M.* × *giganteus* is an active area of research in North America, but very little work has been published to date.

Ways and methods to store Miscanthus biomass

The primary objective in storage is to maximize biomass quality while minimizing costs and dry matter losses. Methods used for Miscanthus bale storage on the farm include the following:

- Storage in open air without covering
- Storage in open air covered with plastic sheeting
- Storage in open air covered with organic materials
- Storage in farm buildings

For storage in open air without covering, ambient moisture can penetrate the pile to a depth of 500mm up to 1 m, and this may result in quality and mass reduction. The covering of biomass piles (e.g. silage) with plastic is a common agricultural practice; covering of piled Miscanthus bales may be labour-intensive and costly depending on the volume of biomass and weather conditions (Lewandowski et al., 2000).

Yield potential of Miscanthus

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). Table 1.3 provides examples of Miscanthus yields in different global locations. Dry matter yield of *Miscanthus x giganteus* in the establishment year is typically insufficient to merit harvest but yield increases each year thereafter reaching maximum potential by year three or four. European research has shown dry matter yields from 11.2 to 24.6 tDM/ha with an average of 17.9 tDM/ha (non-irrigated, fully-established crop). The highest yields are reported in southern Europe, generally south of 40° N latitude. US Research has shown dry matter yields from 22.4 to 33.6 tDM/ha (Illinois). Yields, however, decrease at more northerly latitudes. Yield trials are currently underway in Iowa, Illinois, Ontario and many other jurisdictions within North America. Preliminary yield results in Ontario range between 20 and 21 tDM/y within two years of establishment. A summary of yields in different regions of the world is presented below:

Table 1.3. Miscanthus yields by region

Country	DM yield [tDM/ha/yr]
Denmark	**5- 15**
Germany	**4- 30**
U.K.	**10 - 15**
Switzerland	**13 - 19**
Austria	**22**
Spain	**14 - 34**
Greece	**26 - 34**
US	**11-44**
Canada	**6-33**

Uses of Miscanthus biomass

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 and bioethanol production. The principal aim of developing Miscanthus production in Ontario is for electricity and heat generation.

Technical challenges, limitations and risks to commercial production of Miscanthus

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. For example, At the University of Guelph research station in Elora, the Miscanthus cultivar "***Amori"*** appears to be doing better than other cultivars because of its higher ability to withstand winter cold and resistance to lodging. The giant Miscanthus ***"Freedom",*** developed at the Mississippi State University, is a better performer in southeast USA and is the only cultivar suitable for that area. 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; this is discussed in more details in Chapter 4.

Weed control

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). In Miscanthus check plots with no weed control, Anderson et al. (2010) reported that this significantly reduced the number of tillers per plant and above-ground biomass production, confirming the need for weed control during establishment. The need for registering and use of both pre- and post-emergence herbicides is very crucial in controlling weeds in pre-established Miscanthus plots. 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 centres around its post-harvest losses in storage. There are a number of issues associated with biomass storage, both at the farm-gate level and 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). The decomposition 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. 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 Jørgensen (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, a greater amount of soil and dust can become attached to leaves and stems, requiring more pre-treatment to remove contaminants. 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, the Miscanthus cultivars being promoted for large-scale production in Ontario produce only sterile seeds 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. For example, 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; this is further discussed in detail Chapter 3.

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). Relevant properties and biomass characteristics of Switchgrass and Miscanthus are summarized in Table 1.4.

Table 1.4. 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

2. Switchgrass (*Panicum virgatum*)

Type of plant

Like Miscanthus, switchgrass is a perennial warm-season rhizomatous C_4 grass. Switchgrass historically has been an important component of the North American tallgrass prairie, usually grown on marginal lands not well suited for conventional row crops. Switchgrass can tolerate soil water deficits and low soil nutrient concentrations (Sokhansanj et al., 2009). Cultivar selection, crop management decisions and expectations regarding biomass yield will depend to a great extent on geographic location (Parrish and Fike, 2005). 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 can grow to more than 3 m in height and develop roots to a depth of more than 3.5 m. Switchgrass is not well adapted to cold climates, and therefore is less productive in regions with less than 2500 corn heat units (CHU) (Jannasch et. al., 2001); it however performs better under conditions that are marginal for corn and soybean production. 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.

Origins and global distribution

Switchgrass is native to North America where it occurs naturally between latitude 30°N and 55°N. 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).

Varieties/germplasm for biomass production

Two distinct forms, or ecotypes of switchgrass, 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). The distinction between the two switchgrass ecotypes is summarized as follows:

Lowland type

- Coarse stems
- Higher yielding
- Bunch-type growth habit
- Low winter hardiness

Upland type

- Fine stems
- Lower yielding
- More spreading habit
- Higher winter hardiness

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. 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.

Soil and climatic conditions suitable for switchgrass

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 production of switchgrass on clay soils could result in higher silica uptake in these soils (Samson and Mehdi, 1999; Elbersen et al., 2002). Samson et al. (1999) reported that the ash content of switchgrass grown on sandy loam soils was 15% below that of clay loam soils in eastern Canada. 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. Switchgrass seed is fairly small and, therefore, ensuring good contact between seeds and soil after planting is, highly recommended on all soil types, especially on clay soils. 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. 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.

Switchgrass seldom responds to K and P fertilizer as it has a large root system that scavenges nutrients deep down the soil profile 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).

Optimal planting dates/times

Seeding should be performed in the spring 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). Research conducted in eastern Canada indicates that maximum production is first attained during the third growing season (Samson, 2007).

Switchgrass Establishment

Switchgrass is propagated by seeds, which is an advantage over Miscanthus. Thus, the establishment cost of switchgrass could be as low as 10% that of Miscanthus (Christian et al., 2003). The 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. 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.

Nitrogen fertilization is not required 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 (OMAFRA, 2010), 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 is slow to form a canopy and therefore weed control is very critical to achieving a successful establishment. It is recommended that fields be sprayed with broad spectrum herbicide to eliminate perennial weeds such as quackgrass (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).

Post-establishment fertilization & weed management

Research reports indicate that over-fertilization with N usually results in crop lodging, which ultimately results in yield reduction and harvesting difficulties (Samson 2007). 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).

Pest and disease Control

There are currently no recognized major insect threats to switchgrass. However, there are reports of grasshoppers, stem-boring moths (Northern Great Plains), nematodes (Texas), crickets and corn flea beetles causing minimal damage Christensen et al. (2010). Diseases such as rust, spot blotch, smuts, barley yellow dwarf virus and Panicum mosaic virus have all been reported in switchgrass. In general, southern or lowland varieties tend to be more disease resistant than upland or northern varieties. In trials, EG 1101 and EG 1102, lowland varieties from Blade Energy Crops, have both shown increased resistance to rust diseases

(*Puccinia* spp.) relative to *Alamo and Kanlow*, the respective cultivars from which they were derived.

Optimal times to harvest, and ways and methods to harvest and store switchgrass

Date of switchgrass harvest affects both biomass yield and quality. 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 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. Previous studies by Sanderson et al. (1999) and Vogel et al. (2002) indicated that yields decline by approximately 15% from August to November, coinciding with the transfer of nutrients from above ground to below storage (Parrish and Wolf, 1992, 1993).

Table 2.1 provides a summary of the effects of delayed harvest on elemental composition of switchgrass. Switchgrass harvested in the fall can have high levels of Cl, K, S and N; however, overwintering is effective in significantly reducing these most of these elements.

Table 2.1. Effects of delayed harvest on elemental composition of switchgrass (Nicola Yates, 2003-unpublished data)

Harvesting date	N (%)	Ca (%)	K (%)	Cl (%)	S (%)
July	1.35	0.49	1.33	0.26	0.11
August	0.78	0.50	0.98	0.22	0.08
November	0.45	0.59	0.30	0.10	0.06
December	0.46	0.59	0.20	0.06	0.08
February	0.53	0.65	0.10	0.02	0.08

Switchgrass can be harvested with traditional *hay mower/swather and baler* (large round bales or large square bales) (See Figure 2.1). Use of a mower-conditioner, instead of a conventional mower, and raking into windrows can speed drying. In fields with high yields, however, windrows can be too large for proper handling with haymaking equipment; in such cases, it may be best to let the material dry in the mown swath before baling. Harvesting mown switchgrass with a silage chopper is an alternative to baling that can speed loading, unloading and processing for bioenergy applications. The preferred package is the large square bales because they are easier to manage for transportation and long-term storage. Losses of biomass occur during field operations (e.g. mowing/cutting, baling); Sanderson et al., (1997) reported a 5% biomass loss from conventional fall harvesting of switchgrass (mower and baler) over a two-year study.

A study conducted by REAPCanada (Girouard and Samson 1996) found that conventional spring harvesting (mower and baler) of switchgrass resulted in a 45% loss of biomass (32% as mowing losses and 13% as baling losses). Baled switchgrass may be stored unprotected outside in dry areas. In areas with high rainfall (> 76 cm), a significant amount of dry matter loss can be expected. Storage in barns reduces biomass losses but increases overall production costs.

Yield potential

Switchgrass yields are largely determined by seed variety, length of the growing season, maturity of the stand, quality of the land, and the availability of water and nutrients. Preliminary studies on yields in Ontario indicate that, once fully established, switchgrass can produce 8-12 tDM per hectare per year (Samson, 2007); yields of 8.9 to 10 tDM/ha have been reported by Don Nott, an Ontario switchgrass farmer. 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 identified ecotype, temperature and precipitation 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. Research is ongoing to optimize the yield and quality of switchgrass through both variety improvement and harvest management.

Table 2.2. Switchgrass yields by region

Country	DM yield [t/ha/yr]
The Netherlands	**4 - 9**
U.K.	**5 - 12**
Italy	**5 - 22**
Greece	**15 - 24**
USA	**9-22**
Canada	**8-13**

Uses of switchgrass biomass

Switchgrass can be used in a variety of agricultural and energy markets (Samson, 2007; Girouard and Samson, 2000). Switchgrass biomass can be used for thermal conversion to electricity and heat and also has potential to be a fibre source for paper pulp production. The current major interest, in Ontario, is its use as a commercial *fuel pellet* for heating. On-farm use of such fuel pellets 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. 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).

Technical challenges, limitations and risks to commercial 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. 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. 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.

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.

3. Reed canarygrass *(Phalaris arundinacea L.)*

Type of Plant

Reed canarygrass (RCG) is a Winter-hardy, highly productive and durable C3 grass specie (C_3 plants are less efficient in photosynthesis compared to C4 plants). Reed canarygrass is a cool-season C3 grass species. It has historically been important for grazing, hay production, and soil conservation (Carlson et al., 1996; Sheaffer and Marten 1995) and in some world regions still used as fodder crop. It has relatively high biomass yields (Jasinskas et al., 2008; Marten et al., 1979; Marten and Hovin, 1980) and is therefore receiving increasing attention as a bioenergy feedstock (Wrobel, 2009). Reed canarygrass spreads by rhizomes and forms a solid sod. It is best known for its ability to tolerate poorly drained soils and prolonged flooding, and because of its deep-root system, RCG is more drought resistant than other grasses. RCG can provide high yields on well-drained or even droughty soils; this makes it relatively more productive in the summer relative to other cool season grass species. In Finland, reed canary grass has been cofired with wood chips or peat to generate electricity since the late 1990s (Pahkala et al., 2008). Dedicated reed canary grass feedstock production areas in Finland increased from 500 to 17,000 ha between 2001 and 2006, providing approximately 10% of the feedstock for four power plants.

Apart from its inherent productivity, reed canarygrass makes an appealing biomass crop for several reasons : (1) as a cool season grass, it can be harvested in early summer when warm season grass biomass is not available, facilitating a constant feedstock flow to the bioreactor or power plant furnace (Lavergne and Molofsky, 2007) (2) reed canarygrass biomass increases linearly with applied nitrogen (AOSA, 1998; Cherney et al., 2003) (though fertilization with high levels of nitrogen is generally undesirable, disposal of manure from intensive, industrial livestock and poultry farms, or of municipal wastewater present situations where the ability to take up high nutrient levels is necessary (Casler, 2009), and (3) reed canarygrass can improve the structure of clay-based soils (Lindvall, 1997). Reed canarygrass is classified as an invasive species in many states of the United States.

Origins and global distribution

Reed canarygrass is native to the temperate regions of Europe, particularly Nordic and Scandinavian countries. Reed canarygrass is the most potential energy crop in Finland and currently has 20,000 ha in area of production. It has circumglobal distribution in the northern hemisphere, and is broadly adapted to many stresses including flooding, drought, freezing, and grazing. As such, it can be found in a wide array of habitats, including wetlands, riparian zones, stream banks, irrigation channels, roadsides, forest margins, and pastures (Casler et al., 2009).

Varieties/germplasm for biomass production

Reed canarygrass is propagated with seeds. Common cultivars for biomass production in North America include ***Bellevue, Palaton, Marathon, Vantage and Venture*****.** In Canada, research trials of RCG reported average yields of Palaton to be 9.5 t/ha and 8.0 t/ha in Southern and Northern Ontario, respectively (OMAFRA Report, 2011).

Soil and climatic conditions suitable for RCG

Reed canary grass grows well on most kinds of soils (from sandy to mostly clay), and is one of the best grass species for poorly drained soils because it tolerates flooding. However, the best yields have been recorded from moist fine sand and loamy soils. It grows in slightly acid to neutral soils (i.e. pH of 4.5-8), but is intolerant of saline soils. In North America, RCG has traditionally been seeded on poorly drained pastures, where it is difficult to grow other species; it is therefore good for marginal lands.

Optimal planting dates/times

In North America, RCG is planted in early spring or late summer. The best periods for planting are between mid-April and early June and between mid-July and mid-August (Johnson, 2011). However, late-summer seedings are often more successful because weeds are less of a problem.

Reed canarygrass Establishment

Reed canarygrass is propagated by seeds; however, it is slower and more difficult to establish RCG than other grasses. It is not very competitive in the year of seeding, but once established reed canarygrass is very aggressive (Johnson, 2011). In legume mixtures, a strong reed canarygrass presence may not occur until the third year, but will eventually predominate. This slow establishment means reed canarygrass is not well suited to short, three-year alfalfa mixture rotations, but it can work well in longer rotations. Seedling vigour is poor, so frost seeding, interseeding into established stands and fall seeding are usually not recommended. Seeding is most successful with conventional tillage, but can work in no-till systems as well. A firm, well prepared, packed seedbed is important. Best stands of reed canarygrass are obtained when sown not deeper than 1.3 cm in a well-prepared, firm seedbed. This is best accomplished with band seeders equipped with press wheels. Other seeding methods can be used, but chances of obtaining thick stands and vigorous growth in the seeding year are reduced (Hall, 2010). *Cultipacker seeders* and grain drills work well if the seedbed is firm and the seed is covered to a depth not exceeding 1.3 cm. Caution must be used not to bury the seed after broadcast seeding. Seeding rates are usually 10-12 kg/ha in a pure stand. Weed control is important to minimize competition. Reed canarygrass can be slow to establish and may fail when weed competition is severe during establishment. Grass weeds are especially harmful. It is recommended that if a late-summer seeding is planned, the seedbed be prepared 2 to 4 weeks ahead of seeding to allow the soil to become firm and provide an opportunity to accumulate moisture in the seedbed (Hall, 2010). Seeding times vary from location to location. For example, the best seeding time is before August 15 in northern Pennsylvania and September 1 in southern Pennsylvania. The best planting date for RCG in Ontario is still unknown and needs to be established for the various regions of the province.

Post-establishment fertilization and weed management

Reed canarygrass responds well to adequate fertility, particularly N, and can be a useful tool in nutrient management (Russelle et al., 1997). Pure stands respond well to split nitrogen applications, resulting in increased yield and protein. In a Minnesota study to evaluate the response of reed canary grass to liquid dairy manure and N fertilizer, Russelle et al. (1997) reported that the plant tolerated high rates of slurry addition in clay loam soils; fertilizer N rates greater than 224 kg/ha did not increase yields on loamy sandy soil.

Optimal times to harvest, and ways and methods to harvest and store RCG

Mowing and windrowing are the principal methods of harvesting RCG. In Sweden, disc mowers are commonly used to mow RCG. Use of a mower conditioner resulted in a 45% loss of biomass (32% as mowing losses and 13% as baling losses) with RCG (Hemming, 1995). mower-conditioner is ideal in terms of biofuel quality (Hadders and Olsson, 1997; Pahkala et al., 2007) cited in Wrobel (2009). Studies in Sweden also identified a spring (after snow melt) harvest as ideal for energy production. An over wintered standing crop has a lower moisture content at spring harvest, commonly 10-15 %, reducing the cost incurred by drying. Macro and micro nutrients are also returned to the roots and soil through the winter this is beneficial to soil nutrient status and reduces the production of undesirable by products during biomass combustion. However, a recent study by Tahir et al (2010) indicated that two harvests per year—one in late spring followed by a second in autumn following a killing frost—is the most reliable harvest method to maximize yield across three very disparate sites in the upper Midwestern USA (covering Iowa and Wisconsin). The study also revealed that harvest after snow melts has two problems. First, harvesting lodged biomass requires machinery that can lift material off the ground; considerable yield loss would be expected and contamination with soil is likely. Second, soils are typically saturated at this time of the year, and field operations can be difficult. Shinners et al. (2006) reported that DM yields were reduced by 26% as a result of late harvesting.

In most parts of the world, RCG biomass is stored in round bales. Dry RCG is not very easy to compress and so wrapping with nets or ropes is recommended. The bales may be stored outdoors or under cover. In the US, Shinners et al (2006) reported that bales stored under cover averaged 3.0% DM loss, whilst dry round bales stored outdoors for 293 to 334 days averaged 3.8%, 4.8%, 7.5%, 8.7%, and 14.9% DM loss for bales wrapped with plastic film, breathable film, net wrap, plastic twine, and sisal twine, respectively. The study also reported that the most uniform dry biomass feedstock was generated by storing dry bales under cover.

Yield Potential

Table 3.1 shows the yield potential of RCG in different parts of the world, depending on the number of cuts per annum**.** The average yield of Palaton in Southern Ontario trials is

9.5 t/ha; in Northern Ontario trials, it is 8.0 t/ha (Chisholm, 1994). Highest yields of RCG are obtained when harvested at heading (Hall, 2008). There are only slight differences in yields among cultivars.

Table 3.1. Yield potential of RCG in different regions

Area	**Number of cuts**	**Yield t/ha DM**
USA	**3**	**11**
USA	**1**	**4.4-8.6**
Canada	**3**	**9.5-12**
Sweden	**2**	**10**
UK	**1**	**4**

Uses of Cannary grass biomass

RCG can be used for pasture, hay or silage (Hall, 2008). Recently, RCG has been considered as an industrial crop for bioenergy production, and as a source of short fiber for paper production.

Technical challenges, limitations and risks to commercial production of Reed Cannary Grass

Reed canarygrass is classified as an invasive species in many jurisdictions. It is therefore recommended that prospective growers check with their local extension agencies before planting it. Preliminary evidence in the USA indicates that RCG has higher than desirable levels of silica (Cherney et al., 1991) chlorine, sulphur, alkali metals and nitrogen (Carlson et al., 1978) However, delaying harvest of material from fall to late winter or early spring before regrowth begins can significantly depress the levels of undesirable constituents (Carlson et al., 1978; Hadders and Olsson, 1997); Landström et al., 1996) except N and SiO2. In a USA study by Tahir et al. (2010), it was reported that the N concentration in RCG biomass was highest in spring, intermediate in the fall, and lowest in winter biomass, and that a strong management x location interaction was present. Silicates constituted a higher percentage of ash in the Spring than the other harvests (in the Fall or Winter) (Tahir et al., 2010). By implication, delayed harvesting would not leach out excess N and silicates from RCG biomass. In general, biofuel quality is greatly improved by overwintering biomass, but the potential for harvest problems due to lodging and unfavorable soil moisture in early spring makes this management strategy undesirable for RCG.

4. High-biomass sorghum (HBS) *(Sorghum bicolor L. Moench)*

Type of Plant

Sorghum is a versatile, energy efficient C_4 plant that belongs to the family *Graminae*. Currently, sorghum is the fifth most widely grown and produced cereal crop in the world (Rooney et al., 2007). It has high water-use efficiency; excellent drought tolerance, the ability to withstand water logging, and the ability to *ratoon* (regrow after cutting). Sorghum is however highly frost sensitive. As an annual crop, it can be most responsive to changes in production needs and demand. There are three major types of sorghum: grain sorghum, sweet sorghum, and forage and cellulosic/high biomass sorghum (HBS). The grain sorghum type is high in starch that may be used like corn for producing ethanol. Sweet sorghum is a specific type of sorghum that accumulates high levels of sugar in the stalk of the plant that is used as an alternative to sugarcane in producing syrup and sugar (Reddy and Reddy, 2003). High biomass sorghum (HBS) is the third type of sorghum, and is purposely grown for its biomass for energy production because of its high content of structural carbohydrates (cellulose, hemicellulose and lignin). HBS is typically late or nonheading photoperiod-sensitive (delayed flowering) hybrids. HBS is similar to forage sorghum types, but with greatly enhanced biomass yield potential (CERES, 2010). The HBS germplasm does not transition to the reproductive phase of growth and is said to be photoperiod sensitive. HBS constitutes the focus of this review. Below is a picture of the three types of sorghum. The interest in HBS for bioenergy production is based on factors such as high yield potential and composition, water-use efficiency and drought tolerance, established production systems, and the potential for genetic improvement using both traditional and genomic approaches.

Figure 4.1 Types of sorghum *(from Rooney et al., 2007).*

In the *left foreground* of Fig.4.1 is a typical ***grain sorghum hybrid***; photoperiod ***high biomass sorghum hybrid*** is in the *left background*. On *the right is* ***sweet sorghum*** cultivar developed for **s**yrup production, but also has potential for ethanol production. Sorghum is highly productive and serves a unique production niche of being an annual crop designed to fit into crop rotation schemes. While it can be successfully produced in a wide range of environments, its production is usually associated with hot and dry subtropical and tropical regions because of its high water-use efficiency and drought tolerance, established production systems and the potential for genetic improvement using both traditional and genomic approaches. Sorghum is also fairly tolerant to poorly drained soils and could be widely used on marginal lands, a practice that would not affect the production of current crops (Rooney, 2007).

Origins and global distribution

Sorghum evolved and was domesticated in arid areas of north-eastern Africa; it has been found in archaeological excavations estimated to be over 6000 years old. After its domestication, the use of sorghum in agriculture spread across Africa and into the continent of Asia through traditional trade routes (Kimber, 2000). As it moved to new regions, new domesticated varieties were selected that were specifically adapted to each new environmental region. Compared to Africa and Asia, the species is relatively new to the Americas and Australia, arriving in those regions in the past 200 to 300 years. This process of domestication, combined with occasional intermating and selection of landraces for different regions, has resulted in an extremely wide variation within domesticated sorghum that has many different end uses (Rooney et al., 2007). As a biomass crop, HBS can be grown as far north/south as latitude 45°.

Varieties/germplasm for biomass production

Interested growers have different HBS hybrid types to choose from: *Sorghum x sorghum* hybrids result from the cross between two sorghum parents. These hybrids have the most promising yield potential. According to a recent CERES Report (CERES, 2010), currently available HBS hybrids are designed for single-harvest production systems that maximize yields per unit land area while minimizing costs associated with crop inputs and management. Examples of the newest hybrids include ES 5200 and ES 5201. Another hybrid type is *sorghum x Sudangrass* hybrid developed from the cross of grain sorghum female parent and a Sudangrass male parent; this hybrid has finer stems and prolific ratooning qualities that allows for multiple cuts throughout the season. Pure Sudangrass varieties are not recommended for bioenergy production. Selection of a particular HBS hybrid or variety would depend on traits such as adaptability (e.g. tolerances to disease, temperature, soil conditions and other environmental factors), maturity (regulated by photoperiod/day length or heat units), and harvesting time (Rooney and Aydin, 1999; Monk et al. 1984).

A new high-biomass trait named *'Skyscraper'* provides a significant boost to overall biomass yield potential (CERES, 2010). This trait was developed through genomics-based plant breeding; Hybrids ES 5200 and 5201 both exhibit the Skyscraper trait. The 'brown midrib trait' (BMR) hybrids have altered lignin content that improves the digestibility when used as animal feed; however, current results indicate that sorghums with the BMR trait tend to have higher risk of lodging and therefore reduced yields. Such a hybrid is therefore not suitable as a bioenergy feedstock. There are currently no commercially available sorghum hybrids with traits developed through biotechnology.

Soil and climatic conditions suitable for HBS

Sorghum adapts to diverse soil types (from heavy clay or to light sandy soils), and can also withstand drought. For good performance however, sorghum prefers well-drained soils as well as deeper soils that support its extensive root system. Sorghum is highly amenable to production and cultivation systems currently used around the world. When appropriate, the following tillage practices are recommended for HBS: no-till, strip till, and conservation tillage. It is recommended that conventional tillage be used with great caution as excessive tillage can result in topsoil erosion, weed pressure and the release of greenhouse gases (TAES, 2006).

Optimal planting dates/times

Sorghum seed germination requires at least 16^{o}C to 18^{o}C soil temperature, and optimal soil temperatures for germination and growth range between 21^{o}C to74 ^{o}C. Since sorghum is very frost sensitive, it advised that planting is commenced only after any risk of freezing temperatures has passed, and only after day lengths exceed 12 hours and 20 minutes for photoperiod-sensitive hybrids; (planting before this time would trigger early flowering with subsequent low biomass yield (CERES, 2010).

Establishment of High-biomass Sorghum

Successful HBS establishment involves adoption of agronomic practices that may vary by geographic region, local cultural practices, equipment and existing cropping systems. Bioenergy sorghum varieties are generally planted in rows, using either a row-crop planter or conventional or no-till drill. For heavier to medium soils, planting depth should be 2cm 3cm. In lighter sandy soils, planting may be done to depths of up to 4.5cm. The optimum average seeding rate for sorghum grown for biomass is 247,000 seeds/ha, but this value can be as high as 296,000 seeds/ha and as low as 185,000 seeds/ha depending on input and management scenarios; 50cm or 76cm row spacings are most commonly used for bioenergy crop production (CERES, 2010). A proper match between planting equipment and seed size is considered important for successful stand establishment. Sufficient moisture at seeding is recommended to reduce the risk of stand failure due to subsequent seed /seedling death. Sufficient soil moisture is critical at establishment and in early growth stages although overall water use by sorghum is low in the early stages of development (CERES, 2010).

Starting from the establishment period, many different insect pest and diseases can affect the sorghum plant. Common pests of sorghum include seedling cutworms on seedlings, root nematodes leaf and panicle armyworms and sugarcane borers in the stalks. Common diseases that may afflict sorghum include anthracnose, downy mildew and Fusarium. Several standard agronomic practices exist for mitigating sorghum disease and insect pressures; these include seed treatments, crop rotation and the application of crop protection products. For example, sorghum seeds may be treated with fungicides such as *Maxim*, *Apron* and *Captan*, and insecticides such as *Lorsban* before planting. Systemic seed treatments that protect sorghum from certain insects during establishment are also available.

Post-establishment fertilization and weed management

Nutrient management inputs for the production of grain and forage sorghum have been well established (Butler and Bean, 2002), but relatively little research has been completed for HBS production. Studies reported that the continual removal of all stover does have detrimental effects on the biomass yields in subsequent years (Stanley and Dunavin, 1986). The nutrient requirements for sorghum have been summarized by CERES in its report on “managing HBS as a dedicated energy crop (CERES, 2010). According to that report, a typical fertilizer starting recommendation for a sorghum crop is reported to be 54.4kg of N, 29.5 kg of P_2O5 and 54.4kg of K_2O. However, required levels for these nutrients would vary by soil type and local environmental conditions. Post-establishment N deficiency is the predominant soil issue for biomass sorghum production. A standard recommendation frequently cited is 20kg N/tDM removed, but the optimal rate is mainly influenced by sorghum variety, environment and management practices (Buxton et al., 1998). Thus, the standard rate of 20kg N/t DM may be less for good soils under favourable conditions whereas sandy soils or locations with excessive rainfall early in the season can show reduced levels of available N, regardless of initial application rates. In other situations such as multi-cut systems, N requirements may exceed 30kg/t DM.

A strong correlation between water availability and yield has been established for sorghum: sorghum will do best only in areas with at least 76 cm of rainfall/yr, and water use increases later in the crop cycle. During periods of drought, well established sorghum stands tend to become dormant while waiting for additional moisture; once moisture conditions improve, sorghum stand tends to recover rapidly and continue growing (Rooney et al., 2007; TAES 2006). Prolonged periods of drought can adversely affect sorghum biomass yields; under such a situation, supplemental irrigation is recommended to reduce crop loss and even maintain high yield potential (Hallam et al., 2001; Stanley and Dunavin, 1986).

Pest and disease control

Sorghum can be affected by economically important sorghum insect pests throughout its life cycle. Common examples include *Sugarcane aphid, Corn plant hopper, Oriental armyworm Red-headed caterpillars, root nematodes,* and *sugarcane borers in the stalks*. Examples of sorghum diseases include *anthracnose, downy mildew* and *Fusarium*. Many agricultural practices exist for controlling disease and pest build-up in sorghum stands; standard examples include pre-planting seed treatments with agrochemicals, use of disease and pest resistant cultivars, use of natural/biological predators, crop rotation and the application of crop protection products (e.g. Malathion).

Optimal times to harvest, and ways and methods to harvest HBS

In general, harvesting time is dependent on variety, season length time of planting and desired moisture parameters. Optimal harvest time for HBS is typically between July and October in the Southeastern US and as late as March the following year in the northern parts. With currently available equipment, there could be several options for harvesting biomass sorghum. For example, a single cut may be used to achieve maximum biomass yields, while hybrids specially developed with rationing qualities may be cut repeatedly throughout the season to ensure continuity in biomass supply. Thus, in regions with longer growing seasons, this ratoon capability is important in adding management flexibility and extending the harvest season. The ratoon capability in sorghum is genotype dependent; some genotypes ratoon very well while others do not. Miller et al. (1989) identified specific experimental hybrids that optimized yield potential under multicut and single cut production schemes. Mean cumulative dry-matter yields were 22 t/ha, 23 t/ha, and 22 t/ha for harvest sequences of two cuts at 90 days, two cuts at 120 days and 60 days and a single cut (180 days), respectively. In each case, a different hybrid was highest in yield; this indicates that the hybrids should be optimized for specific production and harvest parameters. Management schemes can be developed in some regions to provide near year round delivery of feedstock to the conversion plant. This ***'just-in-time'*** harvesting system minimizes the need for costly and extensive storage. Ratoon growth also provides organic material that, if not harvested, can be returned to the soil to provide important organic material and nutrients for sound crop and soil management. Unfortunately, there has been little to no research regarding the amount of organic matter that should remain on the land in sorghum production systems. However, the regrowth potential of the crop certainly adds a great amount of flexibility to how much and when the organic material should remain on the land.

The two most common methods for harvesting sorghums for biomass are swathing followed by baling or chopping of windows, and direct forage chopping of the standing crop. A key consideration in choosing between the two methods is the optimal final moisture content of biomass for the desired end use, and what level of subsequent drying is needed to achieve it (sorghum's moisture content at harvest can be as high as 80%, and is directly related to hybrid variety, growing conditions, harvest timing and harvest method, CERES, 2010). The first method of swathing/cutting and windrowing for later pickup allows the biomass to be field dried before final pickup and also allows for field storage. Direct forage chopping of the standing crop minimizes dirt in the harvested material but requires rapid processing of the harvested biomass because the sugars present in the freshly chopped material contributes to its degradation. Graphic representation harvesting in motion can be found at the following site provided by *Lance Wells Renewable Energy Ag Energy*: http://www.youtube.com/watch?v=bkbOdMN04N4

Ways and methods to store HBS biomass

Harvest and storage considerations are crucial for any bioenergy crop and no less so for sorghum production. Potential storage options range from ***'just-in-time'*** harvesting to harvest and storage in a silage type system. A popular storage option in the US includes large square baling when moisture content is below 20%. Large, round bales are also possible, although they are less efficient to transport and store. Studies are being conducted to determine the best practice to speed drying time of the sorghum and maximize the water loss of the conditioned sorghum. Procedures are also being developed to increase the dry matter density of the stored material and perfect a bag design for the sorghum modules to decrease the amount of time spent making modules. Currently, little to no research has been completed on the effect of storage options on quality and conversion.

Yield potential of HBS

HBS yields depend on the genotypes and harvesting management systems (e.g. number of cuts per year) used. The ratoon capability (ability of plant to regenerate new plants after harvesting) of sorghum is genotype dependent and impacts yields. For example, in studies conducted in Texas USA, Miller et al (1989) identified specific experimental hybrids that optimized yield potential under multicut and single cut production schemes. Mean cumulative dry-matter yields were 22 t/ha, 23 t/ha and 22 t/ha for harvest sequences of two cuts at 90 days, two cuts at 120 days and 60 days and a single cut (180 days), respectively. In each case, a different hybrid was highest in yield, thus indicating that the hybrids should be optimized for specific production and harvest parameters. Rooney et al (2007) noted that ratoon growth provides organic material that, if not harvested, can be returned to the soil to provide important organic material and nutrients for subsequent crops.

Uses of HBS biomass

HBS biomass is intended to be used as feedstock for producing heat and energy. It is also being considered for use as cellulosic ethanol feedstock.

Technical challenges, limitations and risks to commercial production of High biomass sorghum (HBS)

Sorghum is susceptible to many insect pests and diseases. While the control of these is possible, it adds to the cost of production of the crop. HBS can experience high incidence of lodging. Soil contact during lodging can increase grit and potentially reduce biomass quality. Another important challenge to HBS production is its moisture content at harvest which could be as high as 80%, depending on hybrid variety, growing conditions, harvest timing and harvest method. To overcome this problem, some techniques are being tried to enhance drydown of the harvested biomass material. For example, sorghum stands may be left in the field to allow natural senescing or exposure to a killing frost, which will aid drying (CERES, 2010). Additional drying can be attained through raking to turn or spread out the windrow and allow sun and wind to evenly reduce moisture content. Also, research is ongoing to determine if broad spectrum herbicides can be applied to the stand to terminate growth and encourage drydown in advance of desired harvest time.

5. Poplar (*Populus spp.*) as a bioenergy crop

Type of Plant

Hybrid poplars are closely related to cottonwoods and aspens and are members of the willow family. Willow and poplar species make up the family of the *Salicaceae*, but the hybrids themselves represent crosses among various cottonwood species (Kinney, 1992). Currently, hybrid poplars are among the fastest-growing trees in North America and are well

suited for the production of bioenergy, fiber and other bio-based products (Pallardy, 2003; Meridian Corp, 1986). Two major characteristic of the poplar as a biomass crop is its rapid initial growth and the ability to *coppice* (make new growth from a cut stump). The productivity of the stool that remains after coppice determines the lifespan of the crop, but poplar plantations are viable for 30 years or more. Poplars can be harvested at short rotations of 8 to 10 years (Isebrands, 2007; Hansen et al., 1993). Globally, poplar plantations have been on the increase in recent years mainly because of the availability of regional subsidies for the establishment of SRC (Zenone et al., 2004). Growing poplars as a crop involves intensive management similar to other agricultural crops. Growing hybrid poplars also entails long term commitment with significant investment and limited economic return for a number of years. However, hybrid poplars can be an attractive crop for landowners and offer new opportunities to diversify income and production (Streed, 1999).

As perennial crops, production of hybrid poplars can offer substantial environmental benefits compared to annual row crop production. Chemical and fertilizer applications are considerably lower, lessening the potential for chemical runoff and leaching. Hybrid poplars, as buffer strips, also intercept runoff of nutrients from fields near streams, rivers and wetlands. As perennial cover, wind and water erosion over the life of the rotation is less than that with annual crops. Hybrid poplars also provide increased year-round habitat for birds and small mammals compared to annual row crops. In addition, poplars also provide enhanced greenhouse gas mitigation (carbon storage), riparian zone protection and wastewater management (Mertens, 1999; Isebrands and Dickmann 2002; Kort and Turnock, 1996).

Varieties/germplasm for biomass production

Hybrid poplars are produced when different poplar species are cross pollinated. Selected seedlings from these crosses can then be propagated vegetatively by taking cuttings and rooting them. Cuttings have identical characteristics to the hybrid parent plant. Many hybrid poplar clones have been tested in various parts of Canada (Barkley, 1983; DeBell and Harrington, 1997). A large number of hybrid poplar species are commercially available, and new hybrids are being continuously created by scientists through crossbreeding. Such new breeds are capable of growing faster and are more drought-tolerant and insect resistant. Common hybrid poplars are crosses developed from *P. deltoids* (eastern cottonwood), *P. trichocarpa*, *P. balsamifera*, and *P. nigra* (black poplar from Europe). The selection of hybrid poplar varieties is site-specific and mixed types are usually used in a field to make the SRC more rust and disease tolerant. Compared to the willow, poplar has a smaller genetic base (Riemenschneider, 2001).

Soil and climatic conditions suitable for hybrid poplar

The following soil properties are most important for growing poplar: soil type and texture, soil moisture and drainage, soil aeration and depth, soil pH, and soil fertility (Isebrands, 2007). Hybrid poplar requires a well-drained and aerated soil with sufficient moisture and nutrients to perform well. For optimum growth the soil needs to be sufficiently deep, have a medium texture with a groundwater table within reach of the roots, preferably at a depth of around 1.00 meter. Heavy soils (clay, clay loam and silty clay loam) are considered less favourable for poplar growth than coarser textured soils (Isebrands, 2007). Also, saline, water-logged, very dry, or gravelly quick draining soils are best avoided; saturated and waterlogged soils during the growing season starve the root systems of oxygen, leading to drought-like symptoms. Optimum soil pH ranges between 5.0 and 7.5. The degree of preparation varies depending on soil type, present crop or vegetation cover and climate of the region (Boysen and Strobl, 1991; Hansen et al., 1983). Intensive site preparation is needed for land in pasture or forage crops to ensure that all perennial plants are controlled. Less intensive preparation is required when the site has been in cereal grains or oilseeds. Standard agricultural equipment can be used for these operations. Poplars thrive under conditions of high light intensity and have an optimal growing temperature of between 15° C to 25° C (TESC-BioSys, www.tsec-biosys.ac.uk). A frost-free growing season of over 150 days is required for optimum growth. Annual rainfall exceeding 600 mm is required for good yield.

Optimal planting dates/times

Optimal planting time for poplar is very crucial to its successful establishment. For example, earlier guidelines that recommended planting in mid-April have led to much dieback in Minnesota due to late spring frost and freezes (Hansen et al., 1994). Poplar is planted in May to early June in North America. Unrooted hardwood cuttings and bareroot stock should be planted when the soil is moist or when rain is expected. Container stock should be watered before planting. Success improves when soil temperatures are above 10^{o}C (50^{o}F). Temperatures of 18^o to 21^{o}C (65^o to 70^o F) are optional. In dry, prairie soils in northwest Minnesota bareroot stock is preferred over unrooted cuttings because the soils dry out before the unrooted cuttings become established .

Establishment of Hybrid poplar

For maximum potential, hybrid poplars require careful management right from the time of establishment. Sites are plowed to a depth of 25 cm and either manually or mechanically planted with 20-25 cm long cuttings at a planting population of 10-12,000 cuttings/ha. Dense plantings are more prone to disease because of reduced air circulation and high humidity. Wider spacings result in faster growth, larger crowns and heavier branches. Cuttings are pushed into the ground with just the top bud showing. Cuttings develop good roots and shoots, but any shading of the shoots from any competing vegetation can be harmful during the first few critical months of establishment, and competition for moisture and nutrients threatens the poplars throughout the establishment phase (till crown closure) (Boysen and Strobl, 1991). During establishment, poplars are intolerant to weed competition. Poplar has a stronger apical dominance than willow and generally produces fewer shoots per stool; therefore canopy closure and shade suppression of weeds may not be as rapid, requiring additional herbicide treatments. In the first year, weeds may be controlled using herbicides and/or mechanical methods. In cases where pre-planting weed control is not possible or is hard to achieve, use of larger rooted sets (*stecklings*) as planting material is recommended. Higher establishment cost of hybrid poplar is a major drawback, in comparison with the herbaceous grasses, to be grown as an energy crops (Oosten, 2006).

Post-establishment fertilization and weed management

Poplars have a high nutrient requirement to maintain maximum productivity. If nutrients or water are limiting, poplar growth is significantly decreased. In most jurisdictions, nitrogen is the most limiting nutrient for poplar culture. In some soils, micronutrients are limiting. Fertilization recommendations are therefore one of the most important aspects of "best management practices" (BMP's). In Minnesota USA, for example, the goal of fertilizer BMP's is for poplar culture to maximize the amount of nutrients taken by poplars, and minimize the quantities of nutrients (especially nitrogen and phosphorous) that run off into nearby streams or to the groundwater (AURI, 1993-1998) . Fertilizers can be applied at any time during the rotation and once the poplars are established soil analyses coupled with foliar analysis are the most economical and effective way of diagnosing nutrient deficiencies. Typical formulations currently used in the Lakes States in the US are granular urea (45-0-0) or liquid urea – ammonium nitrate in solution (28-0-0) in irrigation systems (fertigation). More frequent applications at lower rates such as 56-168 kg/ha (50-150 lb/ac) promote maximum growth and avoid groundwater degradation. The best management practices ("BMP's) for fertilization of poplars in Minnesota is annual applications of 56 kg/ha of nitrogen applied as urea (45-0-0), or as a fertilizer blend (18-18-18) with 2.5% sulfur with diammonium phosphate, urea, potash, and ammonium sulfate (AURI, 1998; MDNR/Wes Min RC & D, 2004).

Competition of any kind will decrease poplar growth and survival. Weed control in the early years of poplar culture is essential. Weed control is easier if good site preparation is done. There are a number of ways to control weeds depending upon the landowner's resources and philosophy. They include hand weeding, cultivation, mowing, cover crops (e.g. use of alfalfa and clover), herbicides and mulching. Herbicides are the most common means of weed control. The choice of herbicide depends on site conditions, weed species, soil type and climate. Pre-emergent herbicides are applied to the soil surface, and rainfall is necessary to move the herbicide into the soil for activation. Soil incorporated herbicides are worked into the soil manually after being applied to the soil surface. Post-emergent herbicides are applied as a directed spray to the foliage of weeds when they are small seedlings and growing actively. Examples of effective herbicides in North America include *Imazaquin* (Sceptor), Pendimethalin (Pendulum) sprayed over the top of newly planted cuttings and *Fluazifop* (Fusilade) for control of grasses. Troublesome invasive weeds like Canadian thistle are controlled with directed sprays of *clopyralid* (Transline).

Post establishment practices such as 'thinning' can be effective in decreasing overcrowding so that larger diameter trees are free to grow and to remove un-merchantable trees for bioenergy or firewood at mid rotation. It is recommended that thinning not be done until the tree crowns have closed and diameter growth rate has declined. Thinning can be accomplished by thinning every other row, or by selectively removing smaller trees to open up the poplar stand. Thinning can be done with traditional harvesting equipment, by horse, or by hand with a chain saw and small tractor. Pruning is the removal of lower dead or dying branches to enhance stem wood quality, and is usually done in late spring or early summer. Poplars sprout readily from the stump or root collar when cut; this resprouting (regrowth) is known as 'coppicing'. Coppicing should be done in the dormant season; coppicing offers the landowner an inexpensive way to re-establish a stand without replanting. Most landowners choose to replant new genetically improved clones rather than coppice. But, coppicing can be attractive because coppice shoots grow vigorously and are very productive. Coppice stands are usually more productive than the original stand in the first 5 years after harvest (Stettler et al., 1996; Oosten, 2006).

Pest & Disease Control

Numerous insects and diseases affect the health of poplars. When poplars are planted in large areas, it is inevitable that insect problems will develop (Ostry et al., 1989; Ostry and McNabb 1986). The major threatening insects in North America include *cottonwood leaf beetle (CLB), forest tent caterpillar, poplar petiolegall aphid, poplar sawfly and poplar vagabond aphid*. The 'best management practices' (BMP) for minimizing insect outbreaks is to plant small block mosaics of several pest resistant poplar clones rather than large monoclonal blocks. Controlling weeds also helps minimize insect outbreaks. The key to minimizing insect pests in poplar culture is to maintain plant and animal genetic diversity and maintain trees in vigorous condition as insects are more common in stressed poplar (Oosten, 2006).

The major diseases of poplar include *stem canker, shoot blight of aspen, fomes root rot fungi, and foliar diseases such as septoria leaf spot, poplar leaf rust, Marssonina leaf spot, and powdery mildew* (Ostry et al., 1989; Callan 1998; and Dickmann et al., 2001). Attacks of poplar rust have led to a reduction or halt in the use of susceptible poplar cultivars in France but were not considered to represent a significant danger in Croatia. The *Marssonina leaf spot* has been reported in Italy, Serbia and Montenegro, Spain and the United States. The *stem canker* is important in Argentina and has been reported to be spreading in Canada. The State University of New York (SUNY) has stopped pursuing the hybrid poplar as a biomass crop due to the occurrence and persistence of *Septoria* stem cankers, which often result in stem breakage leading to lower biomass yields (van Oostern, 2008). The best controls of these diseases include planting resistant clones and maintaining healthy stands.

Abiotic factors affecting poplars include long-term droughts, for example in Bulgaria. Increasing levels of atmospheric CO_2 and ozone, coupled with more variable and extreme weather predicted for the next century, are likely to increase damage by insects and pathogenic fungi to forest trees, including poplars.

Optimal times to harvest, and ways and methods to harvest

There are a whole range options for harvesting poplar; however, for bioenergy, a mobile ***whole tree chippers*** is being used. Harvesting is done in three-year cycles for bioenergy plantings. The three-year cycle runs for only three times (a total of 9 years) in poplar compared to that nine times for willow; this is because of the canker problem with poplar. After each cycle, the practice is to maintain the stand as a coppice stand. Each stump will have multiple stems and the coppice stand will be more productive than the old stand. During harvesting, poplar trees are cut low to the stump to maximize harvest volume and to promote stump resprouting (coppice).

Harvesting of *poplar with whole tree chippers.*

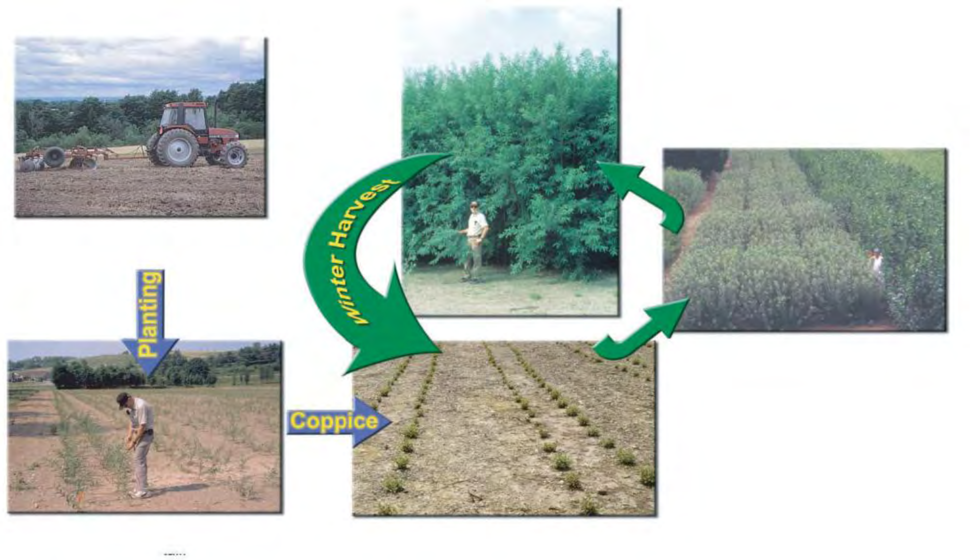
Harvesting is normally done in the winter months to minimize soil compaction and to maximize resprouting. Poplar trees resprout better if cut during the dormant season from November through April. Use of a tracked harvester minimizes compaction (AURI, 1998). One common post-harvest option is to kill the stumps of the former planting with herbicide and replant with new improved poplar clonal stock. When stumps are killed and the site replanted, the new rows are offset and planted within the old rows. This approach eliminates the option of mowing as a weed control strategy because of the presence of stumps.

Ways and methods to store poplar biomass

Cut-and-bundle harvesting of hybrid poplar is a better option for harvesting and storage. This method allows the natural drying of poplar bundles in the field to 30% moisture content before removal from the field.

Yield potential

Growth and yield of poplars depend on geographic location, site quality, clone, age, spacing, and silvicultural conditions. Poplars typically grow in height from 76cm to 213cm per year. Diameter growth ranges from 18 to 23 cm 10 years. Biomass yields range from 5.8 to 10 t/ha in 8 to 10 years. A goal of 13t/ha has been set by geneticists.



Poplar biomass crop growth cycle. *Once the crop is established, three harvests at 3–4-year intervals are possible (indicated by the cycle of green arrows) before the crop needs to be replanted. After each harvest, the poplar resprouts the following spring and develops rapidly.* ***[Adapted from Volk et al (2004)-Front Ecol Environ*** **2004; 2(8): 411–418]**

Uses of hybrid poplar biomass

Pulp, paper and cardboard are the most favoured uses for poplar. Interest in the use of poplar wood as bioenergy has been renewed in recent years. Bioenergy from poplars is a concept that has been around since 1974. Poplar wood, chips, or pellets can be burned directly for energy production or mixed with coal to produce electricity (Licht and Isebrands, 2005). This co-firing approach is a cleaner, cheaper, and more environmentally acceptable than burning coal alone. Another bioenergy application for poplar wood is the small scale close-coupled gasifier for home and farm use. Poplar wood contains between 7000 and 8000 BTU per pound depending on its moisture content. Therefore, a ton of poplar contains nearly 16 million BTU's of energy (Isebrands et al, 1979). That energy equivalent is over 4 million kilo-calories, or 133 gallons of gasoline, or more than 16000 cubic feet of natural gas.

Technical challenges, limitations and risks to commercial production of Miscanthus

A major challenge to large-scale production of poplar is the plant's susceptibility to numerous pests (weeds and insects) and diseases as discussed above. Another challenge is the higher moisture of hybrid poplar at harvest that creates drying and handling issues. Calorific value of hybrid poplar would be reduced with the most cost effective *cut-and-chip* harvesting, when the chips are stored long before being burnt at the energy conversion facility. The removal of poplar stand at the end of its life is more problematic than willow. The rooting system of poplar includes a large taproot that grows down into the soil; removal of the stools will generally require a large excavator.

Mixed energy crops scheme

The latest development in energy crop plantations is that mixed varieties, instead of one strain, are planted in a given plot for two major reasons: better disease and pest control and better pellet quality. Most energy crops are new to commercial agriculture and have not been grown on large scales. The incidence of their susceptibility to insect pest and disease pressures are unknown, and therefore may pose some risk in the future. For example, after a few years of initial success in the production of polar in parts of Europe and North America, various pests and diseases drastically reduced the yields (van Oosten, 2008). Selecting a particular energy crop for large-scale production in a particular location at the initial stages of the bioenergy industry could therefore be a risky proposition and approach. For example, in the case of hybrid poplar, it is recommended that polycultures involving the use of many clones be used in the same field instead of monoculture to mitigate disease and pest build up. Growing more than one energy crop on commercial scale in a region could be an effective strategy to mitigate pest and disease pressures normally associated with only one crop type. Even within the same specie, a mixture of switchgrass varieties for example, adapted to an area can better thrive with seasonal variations and soil conditions than a single variety. This approach would also enable individual farmers to choose the energy crops they can successfully grow based on specific soil types, landscape, micro-climate, existing farm equipment and machinery and crop rotation expectation. Currently, our knowledge of commercial production of any energy crop is limited; the mixed energy crops scheme in a particular geographic region would provide learning opportunities for farmers and allow elimination of problematic energy crop(s) in a particular region in the future (UWO Report, 2009).

An individual energy crop has its own harvesting schedule, handling, storage, pre-processing and fuel characteristics. A mix of different energy crops would allow the supply of biomass at different times of the year, thus ensuring the availability of biofuel to the end-user all-year round. For instance, if the harvesting window for switchgrass is relatively narrow because of delayed harvesting to improve better fuel quality, unpredictable inclement in the region could further curtail the harvesting window. The result of such a scenario is that there may not be enough harvesting machinery and equipment to accommodate all the acreage put under only switchgrass. A mixed energy crop scheme of different crops with different schedules would mitigate such an occurrence and also reduce the possibility of fluctuations in biomass supply. Reduction in biomass yield of a particular energy crop as a result of disease and pest outbreak and or/ unfavourable weather conditions is also a possibility. With high biomass sorghum, an annual, the harvest/supply window can be manipulated through the use of staggered plantings and/or multiple harvests to meet demand. However, growing the crop in succession in the same location could lead to crop-specific nutrient depletion and disease and pest build-up; it would be advisable to rotate it with other crops (e.g. soybean, corn) to mitigate these risks.

Research results in pelleting technology indicate that blends of biomass sources improve the quality of pellets (Evans, 2008). For example, the natural binding properties for making pellets and briquettes from switchgrass appear to be lacking; addition of other biomass types with enhanced binding properties would improve the biofuel quality and durability. In recent years, pellet quality and durability assurance is becoming a major area of research and development priority for successful commercialization of bioenergy.

Selection Matrix of Energy Crops

The purpose of the selection matrix is to aide the prospective farmer make selection of the right type of energy crop based on the soil, landscape and climatic conditions of an area and resources available. For example, RCG may be selected for areas with high soil moisture content (e.g. aerated waterlogged/flooded areas) and where the invasive nature of the plant would not pose a major problem to other species. In areas considered to be marginal in productivity, switchgrass may be selected. Similarly, corn-growing conditions would be suitable for growing Miscanthus, and therefore corn may be replaced by Miscanthus.

Selection Matrix of Energy Crops under Ontario conditions

Attribute	Miscanthus	Switchgrass	RCG	HB-Sorghum	Hybrid Poplar
Available genetic resources	Many varieties available	Many varieties available	Fewer varieties available	Fewer varieties available	Wide genetic base
Yields (tDM/ha)	7-21	5-13	Up to 9	Up to 29	6-10
Optimum harvest time (for combustion quality)	Spring; yield loss=30-50%	Late fall/Mid winter/Early spring; yield loss=up to 45%	Late spring; yield loss = 26%	Mid-summer (July)	Winter months
Harvesting frequency	1/yr	1/yr	1-3/yr	1/yr	biennial
Potential market size	Medium-Large	Medium-Large	Medium	Large	Large
Ease of removal (with chemicals/special equipment)	Yes	Yes	Yes	Yes	Yes
Opportunities for improvement through breeding/genomics	Yes	Yes	Yes	Yes	Yes
Method of propagation/establishment	Vegetative (rhizomes, roots, plugs)	Seeds	Seeds	Seeds	Vegetative (cuttings, coppice)
Rotation time	15-21 years	15 years	10-15 years	Annual	9-12 years
Fertilizer input	Low	Low	Higher than C_4 grasses	High	Moderate?
Known major pests and/or diseases	None	None	None	Many	Many/serious e.g. canker
Recycling of nutrients to roots	Yes	Yes	Retains N in stem	Yes	?
Cold tolerance	Moderate; Nagara is best	Moderate for Upland types	Best adapted	Moderate	Well-adapted
Adaptation to stress (e.g. winter hardiness)	Moderate winters (Nagara is best)	Moderate winters; low moisture	Cold regions; tolerates poorly drained soils	Moderate; very frost-sensitive	Moderate
Adaptability to marginal soils	Moderate	High	High (highly tolerant to soil limitations)	Medium	Medium
Water use	High; considerable yield decline under water-stressed conditions	Low	Medium	Medium	Medium
Required machinery	Normal farm equipment	Normal farm equipment	Normal farm equipment	Normal farm equipment	Special equipment
Harvest requirement	Normal baling	Normal baling	Normal baling	Normal baling	Special harvesting
Risk of it becoming a weed	No	No	Yes, it is a weed	No	No
Erosion control	Very good	Very good	Very good	Very good	Moderate
Runoff potential	Low	Low	Low	Low	Low
Wildlife habitat	Yes, better than annual crops	Yes, better than annual crops	Yes, better than annual crops	Moderate	Yes, better than annual crops
Levels of undesirable elements in biomass	Low	Low	High levels of Si and K	Low	Low

Chapter 2: Densification and processing technologies of energy crop biomass

This chapter reviews biomass densification and processing technologies for combustion energy. The focus is on biomass quality characteristics of the five selected crop species and how these characteristics may impact current methods used for the densification of biomass type. To define biomass quality characteristics, we tabulated available data on *proximate analysis* (moisture content at harvest, fixed carbon, volatile matter and ash content of biomass), *ultimate analysis* (elemental analysis of C, H, O, S, and N), *elemental composition* (includes mainly the oxides of Si, Al, Mg, Na, S, and P as well and Cl) and the *structural carbohydrate contents* (cellulose, hemicellulose and lignin) of the five plant species, where possible.

2.1. Characteristics & Properties of energy crop biomass

Biomass feedstocks exhibit a wide range of physical, chemical, agricultural and process engineering properties. It is these inherent properties of biomass source that determines both the choice of conversion process (e.g. thermochemical, biochemical) and any subsequent processing difficulties that may arise (McKendry, 2002). In general, biomass feedstocks are quite uniform in many of their fuel properties, compared with competing feedstocks such as coal or petroleum. Depending on the energy conversion process selected, particular biomass material properties become important during subsequent processing. This review focuses only on the dry biomass conversion process (i.e. thermochemical processing) of the five selected biomass species outlined above. The main biomass properties of interest relate to moisture content; calorific value (heating value), ash content, alkali content and structural carbohydrate content.

Moisture content

Moisture content is the major factor in determining the net energy content of a biomass source; the lower the moisture content, the higher the heating value or net energy potential. Biomass moisture content also affects the harvesting, storage, pre-processing, handling and transportation of biomass. At harvest, air-dried biomass by natural drying in the field ranges between 6% and 20% moisture depending on the plant species (DEFRA, 2007; Tables 2.1-2.5). However, the moisture content at harvest of biomass sorghum and poplar are higher (>40%), and may require additional drying before processing. The moisture content of raw biomass may be reduced through the following ways: (1) leaving the biomass in the field to dry naturally for a period of time; (2) storing the biomass under shelter; (3) drying the biomass commercially; and (4) using densification technologies to squeeze out the moisture; a full discussion of currently available densification technologies is provided below.

Energy content

The energy content of a material, also referred to as the calorific value (CV), is an expression of its heating value (McKendry, 2002). The net heating value expresses the actual energy available for heat transfer. The difference in available energy is explained by the material's chemical composition and moisture and ash contents (personal communication, Steve Clarke and Fernando Preto, 2011). A biomass fuel's energy content (heating value) is reported on dry weight basis, and normally expressed in 'higher heating value (HHV)' which represents the maximum amount of energy potentially recoverable from a given biomass source (Demirbas, 1997; 2004). However, the actual amount of energy recovered varies with the conversion technology as well as the form of that energy. Almost all kinds of herbaceous biomass feedstocks meant for combustion have energy content that falls in the range of 14-19 GJ/t (compared to that of coal of 17-30 GJ/t).

Biomass composition

Biomass composition varies significantly among biomass species, and the fuel performance of a biomass material depends on this composition. Apart from biomass species (i.e. herbaceous versus woody), other factors such as agronomic management (e.g. use of agro-chemicals, period and harvesting time) and pedo-climatic characteristics (e.g. soil type, rainfall intensity and distribution, etc) can influence biomass chemical composition. Major characteristics of a biomass include the contents of ash, carbon (C), hydrogen (H), nitrogen (N), sulphur (S), oxygen (O) and chlorine (Cl). Biomass chemical composition has direct impact on the combustion process and on harmful emissions; in particular, high levels of ash, S, N, and Cl are undesirable. Selected fuel characteristics of five biomass sources in this review are presented in Tables 2.3-2.7.

Ash

The chemical breakdown of biomass fuel during combustion in air results in the production of a solid residue called 'ash'; ash is thus the non-combustible content of biomass. Ash content is the major difference in composition of biomass fuels and influences the choice of an appropriate combustion and process control technology (Nordin, 1994; Cherney et al., 1988). Recycling of ash to agricultural and forest land would return nutrients to the soil and could contribute to the sustainable use of biomass for power generation; this practice is already being implemented to some extent in some European countries including Sweden, Finland, Austria and Germany. The major chemical components of ash include K, Mg, Si, Cl, Ca, Al, and Fe. Several factors could affect the ash quantity and quality of herbaceous biomass, namely (1) plant type and species, (2) plant fractions growing conditions, (3) harvest time, (4) handling and storage, and (5) pre-processing.

Plant-type: Compared to C4 plants (e.g. Miscanthus, switchgrass), C3 plants (e.g. sorghum, reed canary grass) require more water to produce a similar amount of plant dry matter. As a result, C3 plants generally contain a higher ash concentration as water uptake is directly related to the uptake of Si and other inorganic constituents in plant biomass.

Plant fractions*:* The distribution of ash and specific inorganic components in herbaceous biomass may vary significantly among different plant fractions. For example, Summers et al. (2001) determined total ash and silica in different botanical fractions of rice straw (leaf, stem, node, panicle) and concluded that ash and silica content varied significantly among straw fractions: leaves contained 18-19% total ash (of which 76% consisted of silica), whereas stems contained only 12% ash (with 42% silica).

Growing conditions: For any given species, soil type, particularly the texture, is a very important factor in deposition of inorganic constituents in biomass. For example, Elbersen et al. (2002) determined total ash and nutrient content of five switchgrass varieties on a clay and a sandy soil in the Netherlands and reported that switchgrass grown on sandy soil consistently showed lower ash (51-73% reduction compared to clay soils) and potassium content (16-44%), whereas results for chlorine were variable; the difference in total ash content among these soil types can be largely explained by the higher soluble silica level in clay soils, which results in higher ash levels in crops grown on clay soils. Similarly, Pahkala et al. (1996) reported ash contents of 1.3% in sandy soils, 1.9% in organic soils and 4.9% in clay soils with reed canarygrass in Sweden. Also, the type and amount of fertiliser affects ash content and quality in herbaceous biomass, in particular with regards to K- and Cl-containing fertilizers (Bakker and. Elbersen, 2008).

Harvest time and harvest technique: Both the total amount of ash as well as specific inorganic constituents in herbaceous biomass can be manipulated by the timing of harvesting. Extending harvest dates later in the season generally leads to lower ash content. A number of constituents (e.g. K, Cl) are particularly reduced due to effects of increased senescence and translocation (plant nutrients are removed from leaf and other tissues to under-ground parts), and leaching (removal of soluble constituents by rain, mist or dew). The beneficial effects of leaching on combustion characteristics have been described for many herbaceous biomass types, including rice and wheat straw (Jenkins et al., 1996), and reed canary grass (Burval, 1997). In eastern Canada spring harvested whole plant switchgrass resulted in 2.75% and 3.21% ash on sandy loam and clay soils respectively (Samson et al 1999). However, for Reed canarygrass, silicates constitute a higher percentage of ash in the spring than the other harvests (in the fall or winter) (Tahir et al. 2010; Table 2.1). Efforts to include a time window to allow for leaching by natural means (e.g. rain, dew) are generally referred to as *delayed harvesting, spring harvest, or field leaching*. Delaying harvest however can also have important tradeoffs, such as a high loss of plant matter (which reduces yields considerably) or an increase in total ash (due to losses of organic matter) (Bakker et al., 2004). The selection of mechanical harvesting techniques may affect ash content and composition as well, in particular in field harvest operations that include swathing, raking or curing the biomass prior to collection, which is often performed to enhance field drying or optimize harvest operations. Swathing or raking may increase the amount of soil particles in the biomass, which add to total ash composition (Bakker et al., 2004). Examples of the impact of delayed harvesting on ash quantity and major chemical constituents for Miscanthus, switchgrass and Reed canarygrass are summarized in Table 2.1

Table 2.1. The impact of delayed harvesting on ash quantity and major chemical constituents expressed as % of dry weight). Values are means across locations or cultivars

	Miscanthus[a]		**Switchgrass[b]**		**Reed canarygrass[c]**	
Ash & constituents (%)	F/W-H	D-H	F/W-H	D-H	F/W-H	D-H
Ash	4.0	2.5	3.5	3.45	6.4	5.6
K	0.9	0.4	0.06	0.21	1.23	0.27
Si			1.03	1.12	1.2	**1.85**
Cl	0.4	0.1		0.21	0.56	0.09
Ca				0.25	0.35	0.20
Al						
Fe						
P					0.17	0.11
S	<0.01			<0.01	0.17	0.09
Mg					0.13	0.05

F/W-H: Fall or Early Winter Harvest; D-H: Delayed Harvest

[a]Data for Miscanthus from Lewandowski et al (2003); **[b]**Data for Switchgrass from Xiong et al (2008); **[c]**Data for Reed canarygrass from Burval (1996).

Handling and Storage: Biomass handling after field operations may lead to increases in inorganic constituents in herbaceous biomass. Impacts of long-term storage of herbaceous biomass on ash are generally believed to be small, as long as the biomass is stored at sufficiently low moisture contents(<20% dw.). However, if microbial degradation in stored biomass occurs, the loss of organic matter will lead to an increase in inorganic constituents on a volumetric basis. For wet biomass streams, ensilage techniques have been proposed to allow for longer term storage prior to conversion (Bakker et al., 2004).

Pre-processing: Given the beneficial effects of leaching of inorganic constituents from biomass on ash quality as discussed above, a number of authors have proposed a controlled washing or leaching step prior to conversion to remove troublesome elements from herbaceous biomass. Techniques might include submersion in water, dewatering, and/or drying. Removing elements after initial, primary conversion (e.g. ***char wash***) has been proposed as well Jensen et al (2001). Turn et al. (2009) proposed a combination of treatments that include crushing, imbibition (i.e. adding water to the crushed biomass to facilitate extraction), and dewatering. Constraints for commercial application of leaching as a pre-processing step are the incremental costs of leaching, high water requirements, and reduction of conversion efficiency due to higher fuel moisture content.

In the presence of ash, two unwanted processes can occur during biomass combustion in the boiler: “slagging” and “fouling”. Slagging occurs in boiler furnaces where ash deposits are exposed to the radiant heat of the combustion flames, and fouling refers to the accumulation of ash on the boiler surfaces that impedes and interferes with the boiler’s function. High ash content leads to ‘fouling’ problems especially if the ash is high in K and Cl. Biomass fuels, especially those of agricultural origin, tend to have high ash with high K content. The ash melts at lower temperatures resulting in ‘clinkers’ which can jam furnace elements. Both ‘slagging’ and ‘fouling’ may occur simultaneously when ash is vapourized and condensed in the boiler, resulting in the production of hard formations on heat transfer surfaces. In general, agricultural biomass sources have higher ash content compared to wood sources. However, unlike coal ash which may contain toxic metals and other trace contaminants, biomass ash may be used as a soil amendment to help replenish nutrients removed by harvest.

Elemental composition

Elemental analysis of a fuel, presented as carbon (C), nitrogen (N), hydrogen (H), oxygen (O) and sulphur (S) together with ash content is termed the *ultimate analysis* of the fuel. Biomass elemental composition is varied depending on geographical location, crop variety, climate conditions, soil and agronomic practices, harvest methods and densification methods. Tables 2.1 to 2.5 provide the ultimate analysis of our selected biomass sources. The C content of biomass ranges between 45% and 48%, and coal contains 60% C (Demirbas, 2007). Higher C content translates to higher heating value. The H content of biomass is about 6% (Jenkins, 1998). Higher H contents also lead to higher heating values. The significance of O:C and H:C ratios on the heating value of solid fuels is that the higher proportion of oxygen (O) and hydrogen (H), compared with the carbon (C) reduces the energy value of a fuel, due to the lower energy contained in C-O and C-H bonds than in C-C bonds. These ratios explain why the HHV of coal is higher than those of biomass materials, and why the HHV for poplar is slightly higher than the other four selected species (Tables 2.1-2.5). Biomass N content varies from 0.2% to > 1% (Jenkins, 1998); crop species with high N content may lead to higher N_2O emissions during combustion. Most biomass fuels, including our selected crop species in this review, have S content less than 0.2% and therefore do not contribute significantly to S emissions. Sulphur oxides (SO_x) are formed during combustion and contribute significantly to particulate matter (discussed in more detail in Chapter 3) and acid rain (personal communication, Steve Clarke and Fernando Preto). Biomass materials with high Cl concentrations (1000µg/g or 0.1%) can lead to increased ash fouling and the formation of hydrochloric acid that may cause corrosion of the boiler. Cl contents in the perennial grass species are over 1000µg; those for the annual specie (sorghum) and poplar are less.

The alkali metal (Na, K, Mg, P, and Ca) and Si content of biomass is considered important for any thermochemical conversion process (Nordin, 1994). Monti et al. (2008) reported that understanding the relationships among minerals is of great relevance since the negative effects of some minerals depend on the concurrent presence of others. For example, some volatile elements such as C may cause fouling in the presence of K and Si (Miles et al., 1996); similarly, high Si:K or Ca:K ratios are reported to reduce slagging (Reumerman and Van den Berg, 2002) and (Baxter et al., 1998). In an Italian study by Monti et al (2008), a number of significant correlations have been found between different elements. For example, ash content was found to be highly correlated to C and Ca contents, and to a lesser extent to Na, Si and Cl. Equally, N was found to be positively related to K and P and negatively to Si/K and Ca/K ratios, while Cl was negatively related to Si, Si/K and Ca/K. Also, K was highly correlated to P, and to a lesser extent to Mg, while P was negatively associated with Si/K and Ca/K ratios. The effects of the different biomass elements on the environment and the combustion process are summarized in Table 2.2.

Table 2.2. The effects of ash and biomass chemical constituents on the environment and combustion process

Ash/Chemicals	Effects
Ash	Dust emissions; combustion technology
Carbon (C)	HHV[a] (Higher heating value)
Hydrogen (H)	HHV, LHV[b] (Lower heating value)
Oxygen (O)	HHV
Chlorine (Cl)	*PCDD*/PCDF (Polychlorinated dibenzo-p-dioxin and polychlorinated dibenzofuran) emissions; corrosion, lowering ash-melting temperature
Nitrogen (N)	NO_x, N2O emissions
Sulphur (S)	So_x emissions; corrosion
Potassium (K)	Corrosion; lowering ash-meting temperature; aerosol formation; plant nutrient
Sodium (Na)	Corrosion; lowering ash-meting temperature; aerosol formation
Magnesium (Mg)	Increase of ash-meting temperature; plant nutrient
Calcium (Ca)	Increase of ash-meting temperature; plant nutrient
Phosphorus (P)	Plant nutrient
Silicon (Si) in ash	Si in combination with K and Na can lead to the formation of low-melting silicates in fly-ash particles; herbaceous biomass ashes containing low concentrations of Ca and high concentrations of Si and K cause 'sintering' (the process of densification of porous solids responsible for hardening of fume deposits.

[a]HHV: is the gross amount of heat released during the combustion of a specified amount of biofuel.
[b]LHV: is the net amount of heat released during the combustion of a specified amount of biofuel.
Source: ***Adapted from Hartmann (1998).***

In contrast to their fairly uniform physical properties, biomass fuels are heterogeneous with respect to their chemical elemental composition because the mineral content of biomass is soil-type dependent. For example, clay soils have higher monosilicic acid $[SiO_x(OH)_{4-2x}]_n$ content than sandy soils which result in more Si uptake into plants creating higher ash fuels. The reaction of alkali metals with silica (SiO_2) present in the ash produces a sticky, mobile liquid phase that can lead to blockages of airways in the furnace and boiler plant. Both Miscanthus and switchgrass have comparatively higher Si or alkali metal contents and therefore require special precautions for harvesting (e.g. delayed harvesting), processing and combustion equipment.

Management practices to reduce ash and elements for better combustion

Various agronomic and management practices may be used to reduce contents of ash and primary elements that interfere with the combustion process. These strategies include (1) crop selection, (2) modifying growing conditions, (3) plant fractionation during harvesting, (4) manipulation of harvesting time and (5) minimizing soil contamination. In general, warm-season grasses (e.g. switchgrass) have lower ash content compared with cool-season grasses (e.g. RCG) (Samson and Mehdi, 1998). With regard to growing conditions, soil type significantly impacts biomass ash content. For example, high ash levels are found in crops produced on soils with higher clay components than crops produced on sandy soils because of higher alumino-silicates in clay soils. The distribution and composition of ash varies among different plant fractions, and ash levels are highest in grass leaves and lowest in stems (Samson et al., 1999b). Harvesting biomass with higher stem fractions can therefore reduce the plant's ash concentration and improve the biomass quality for combustion. Delayed harvesting by overwintering results in minimizing ash, Cl and K content of harvested biomass; however, this strategy may lead to biomass losses of 20-50% mainly due to erosion. Since soil particles greatly increase the ash concentration of biomass, contamination of crop biomass by soil particles during harvesting and/or on-farm storage can lead to increases in biomass ash content. To minimize this, it is recommended that proper mechanical harvesting techniques be used to avoid stirring the soil. For example, biomass may be cut with higher stubble height.

Table 2.3. Selected Fuel Characteristics of Miscanthus x giganteus (dry matter)

Proximate Analysis		Ultimate Analysis		Ash Elemental Composition		Content of Structural carbohydrates	
	(wt. %)		(wt. %)		(wt. %)		(wt. %)
Fixed carbon		Carbon	48.4	SiO_2	39	Cellulose	45
Volatile matter	82.1	Hydrogen	6.3	Al_2O_5	1.6	Hemicelluloses	30
Ash	1.5	Oxygen	43.3	TiO_2		Lignin	21
Moisture at harvest	30-50	Nitrogen	0.3	Fe_2O_3	1.1		
		Sulphur	0.1	CaO	8.6		
		Ash		MgO	5.9		
		Moisture		Na_2O	2.2		
		HHV[MJ/kg]	19.58	K_2O	27		
		Chlorine	0.13	SO_3	4.9		
				P_2O_5	6.3		
				CO_2	0.5		
				Cl	3.5		

Source: Adapted from: Phyllis database (http://www.ecn.nl/phyllis/) Energy Research Centre of the Netherlands (ECN); REF for the STRUCTURAL CARBOS: http://pubs.acs.org/doi/full/10.1021/ef700776w

Table 2.4. Selected Fuel Characteristics of Switchgrass (dry matter)

Proximate Analysis		Ultimate Analysis		Ash Elemental Composition		Content of Structural carbohydrates	
	(wt. %)		(wt. %)		(wt. %)		(wt. %)
Fixed carbon		Carbon	47.5	SiO_2	61.6	Cellulose	32-36
Volatile matter	82.9	Hydrogen	5.8	Al_2O_5	1.3	Hemicelluloses	26-28
Ash	3-5[a]	Oxygen	43.6	TiO_2	0.2	Lignin	17-19
Moisture at harvest	12-14[b]	Nitrogen	0.36	Fe_2O_3	1.1		
		Sulphur	0.05	CaO	11.1		
		Ash		MgO	4.9		
		Moisture		Na_2O	0.6		
		HHV[MJ/kg]	18.6	K_2O	8.2		
		Chlorine		SO_3	0.8		
				P_2O_5	3.1		
				CO_2	NA		
				Cl	NA		

Source: Adapted from: Phyllis database (http://www.ecn.nl/phyllis/ Energy Research Centre of the Netherlands (ECN); REF for the STRUCTURAL CARBOS: http://pubs.acs.org/doi/full/10.1021/ef700776w
a. At harvest, can be reduced to 20-25% by natural drying in the field [DEFRA, 2007]

Table 2.5. Selected Fuel Characteristics of Reed Canary grass (dry matter)

Proximate Analysis		Ultimate Analysis[b]		Ash Elemental Composition[b]		Content of Structural carbohydrates	
	(wt. %)		(wt. %)		(wt. %)		(wt. %)
Fixed carbon	12.1	Carbon	48.6	SiO_2	50.3	Cellulose	42.6
Volatile matter	82.5	Hydrogen	6.8	Al_2O_5	0.37	Hemicelluloses	29.7
Ash	5.5[a]-9.6[b]	Oxygen	37.3	TiO_2	0.02	Lignin	7.6
Moisture at harvest	4.7	Nitrogen	0.3	Fe_2O_3	0.18		
		Sulphur	1.46	CaO	3.80		
		Ash		MgO	2.40		
		Moisture		Na_2O	0.44		
		HHV[MJ/kg]		K_2O	16.4		
		Chlorine	0.76	SO_3	NA		
				P_2O_5	4.62		
				CO_2	NA		
				Cl	NA		

Sources:
[a]**Bridgeman et al (2008) :** http://www.techtp.com/twpapers2/Torrefaction%20of%20reed%20canary%20grass,%20wheat%20straw%20and%20willow.pdf
[b]**Tahir et al (2011)(Spring harvested):** http://www.springerlink.com/content/b677l7vt2785hj77/fulltext.pdf

Table 2.6. Selected Fuel Characteristics of High-Biomass Sorghum (dry matter)

Proximate Analysis		Ultimate Analysis		Ash Elemental Composition		Content of Structural carbohydrates	
	(wt. %)		(wt. %)		(wt. %)		(wt. %)
Fixed carbon	18.6	Carbon	44.55	SiO_2	NA	Cellulose	27
Volatile matter	72.75	Hydrogen	5.35	Al_2O_5	NA	Hemicelluloses	25
Ash	8.65	Oxygen	39.18	TiO_2	NA	Lignin	11
Moisture at harvest	70-75a	Nitrogen	121	Fe_2O_3	NA		
		Sulphur	0.08	CaO	NA		
		Ash		MgO	NA		
		Moisture		Na_2O	NA		
		HHV[MJ/kg]	16.31-17.39	K_2O	NA		
		Chlorine	0.13	SO_3	NA		
				P_2O_5	NA		
				CO_2	NA		
				Cl	NA		

Source: Adapted from: Phyllis database (http://www.ecn.nl/phyllis/) Energy Research Centre of the Netherlands (ECN); McKendry (2002): http://faculty.washington.edu/stevehar/Biomass-Overview.pdf:

Table 2.7. Selected Fuel Characteristics of hybrid Poplar (dry matter)

Proximate Analysis		Ultimate Analysis		Ash Elemental Composition		Content of Structural carbohydrates	
	(wt. %)		(wt. %)		(wt. %)		(wt. %)
Fixed carbon		Carbon	50.2	SiO_2	5.9	Cellulose	45-56
Volatile matter	84.8	Hydrogen	6.06	Al_2O_5	0.8	Hemicelluloses	18-25
Ash	2.5	Oxygen	40.4	TiO_2	0.3	Lignin	21-23
Moisture at harvest	45-50	Nitrogen	0.6	Fe_2O_3	1.4		
		Sulphur	0.02	CaO	49.9		
		Ash		MgO	18.4		
		Moisture		Na_2O	0.1		
		HHV[MJ/kg]	19.02	K_2O	9.6		
		Chlorine	0.01	SO_3	2.0		
				P_2O_5	1.3		
				CO_2	8.2		
				Cl	NA		

Source: Adapted from: Phyllis database (http://www.ecn.nl/phyllis/) Energy Research Centre of the Netherlands (ECN): http://asae.frymulti.com/azdez.asp?JID=5&AID=28044&CID=reno2009&T=2

2.2. Densification technologies of energy crop biomass

Concerns over the environmental impact of fossil fuel use, security of supply and the increasing cost of petroleum oil have resulted in an increasing desire to develop advanced bioenergy technologies which will ultimately promote the increased use of biomass as a resource for the production of suitable forms of energy, fuel and chemicals. Biomass however has lower energy content than the traditional fossil fuels. A lower energy content implies more biofuel is required to obtain the same amount of energy and also a larger space for storage and higher costs for transportation to processing sites because of the lower bulk density. The goal of biomass densification is to increase both the energy density and the bulk density of biomass. *Energy density* describes the amount of energy stored per unit volume and is often expressed in MJ or GJ/m^3; *bulk density* is defined as the mass per unit volume of a material, and is expressed in kg/m^3. For example, Colley et al. (2006) reported that bulk density of ground switchgrass was 165.5 kg/m^3 and that bulk density of densified switchgrass in form of pellets ranged from 536 to 708 kg/m^3. This section reviews the techniques and technologies currently available for densification processes.

Converting agricultural biomass into a densified form has the following advantages: (1) increase in the net calorific value (heating value) per unit volume, (2) reduced cost and improved ease of storage, (3) improvements in transportation efficiency, (4) decreased losses of biomass through deterioration or spontaneous combustion (5) increased ease of handling if utilized as a biomass pellet/briquette fuel, (6) increase in the efficiency of potential combustion, (7) enhanced uniformity in properties, and (8) the ability to standardize (size and quality) feeding mechanisms for gasifier and other biomass based systems. The main disadvantage to biomass densification technologies is the high cost associated with some of the densification processes.

Densified biomass can subsequently be used as a fuel in a number of applications including co-firing, combined heat and power (CHP), heat production and advanced lignocellulosic biofuel production (biorefining). Currently, biomass is densified by two main processes: (1) mechanical densification that involves applying pressure to mechanically densify the biomass material (e.g. baling, pelletizing, briquetting), and (2) pyrolysis that involves heating the biomass in the absence of oxygen (e.g. torrefaction, slow pyrolysis, fast pyrolysis). Thus, densification process variables that may influence densification results include, pressure and pressure application rate, hold/retention time, temperature and die geometry.

Feedstock variables that may influence densification results include moisture content, biomass particle size, biochemical characteristics, and conditioning. Feedstock moisture content requirements are a function of the feedstock material and the densification process used. For example, compared to herbaceous plants, woody plants (e.g. poplar, willow) contain higher lignin content which contributes to the strength characteristics of densified pellets and briquettes (see tables 2.1-2.5). This section reviews the techniques used for the main densification processes.

2.2.1. Pre-treatment of biomass prior to densification

Pre-treatments may be required to optimize the energy content and bulk density of the biomass material prior to biomass densification. Examples of such pre-treatments include chopping and/or grinding, drying to required moisture content, and conditioning by applying binding agent or steaming. Chopping and/or grinding of raw biomass are required to achieve the following: (1) lower energy use in the densification process, (2) make the material denser, and (3) decrease breakage of the outcome product (Dobie, 1959). Low moisture results in improved density and durability of the biofuel (Shaw and Tabil, 2007; 2005). For most densification processes, the optimum moisture content is in the range of 8-20% (Kaliyan and Morey, 2009). For example, although there may be variances between different manufacturers' equipment, acceptable moisture content for densification of soft wood residues are 9 to 12% for pelleting, and 10 to 15% for extrusion briquetting. Required feedstock particle size is again a function of the densification process used and varies with the specific equipment geometry (e.g., die size). Most compaction techniques require a small amount of moisture to 'soften' the biomass for compaction, but above the optimum moisture level, the strength and durability of the densified biomass is decreased. The density and durability of densified biomass is influenced by the natural binding agents of the material, and the binding capacity increases with a higher protein and starch content (Tabil et al., 1997; Shaw and Tabil, 2006). Thus, for biomass crops with low binding properties, binding agents may be added to increase the binding properties. Examples of such binding agents include vegetable oil, clay, starch, cooking oil and wax. The addition of steam prior to densification can aid in the release and activation of natural binders present in the biomass. For example, the heat produced during pelletizing, along with the heat added in some conditioning (e.g. high quality steam) assists the release of lignin which then acts as a natural binder for the material (Tabil, 1996). Partial breakdown of lignin may occur during particle size reduction (e.g. grinding), also promoting binding.

2.2.2. Mechanical densification technologies

2.2.2.1 Biomass Bales

Bales are a traditional method of densification commonly used as part of the harvesting process. On the farm, a 'baler' is used during baling to compresses chopped raw biomass. Bales may be square, rectangular or round, depending on the type of baler used. In Ontario, the dimensions of round bales range from 1.m x 1.5m to 1.5m x 1.5m. Large rectangular bales typically measure 0.9m x 0.9m x 1.8m. Round bales are less expensive to produce, but large square bales are easier to handle and transport since they are denser.

2.2.2. 2. Biomass Pelletisation

Compared to raw undensified biomass, pellets are very high in density. Biomass pellets can be made from a number of *comminuted* (finely ground) biomass types, including energy crops. The production of fuel pellets in Ontario began in the early 1970's when Shell Oil built a wood pelletizing plant in Northern Ontario as part of a diversification program (personal communication, Steve Clarke and Fernando Preto). The apparent target market was pellet fuel stoves in rural homes. In recent years, as a result of climate change concerns, more pellet plants have been built. Both plant biomass and wood materials are being used as the raw material.

Pellets are formed by an extrusion process, using a piston press, where comminuted material is forced through round or square cross-section dies and cut to a desired length (personal communication, Steve Clarke and Fernando Preto). The heart of the operation is the ***'roll and die' pellet mill*** which is a well proven and relatively simple machine. In operation, prepared biomass fibre is conveyed into the interior of the rotating cylindrical die and is densified as it is extruded through the die with pressure from the rollers. As no **devolatisation** (removal of the volatile residues) takes place during the pelletisation process, the only mass loss is as a result of moisture loss. However, pelletisation does require energy input at temperatures between 90^{o}C and 150^{o}C. Unlike the torrefaction and pyrolysis processes, the pelletisation process is not able to operate itself sufficiently or autothermally. The pelletization process may be represented as follows:

Stored square bales →bale breaking/chopping →feedstock drying (to moisture levels of 8-12% at 90-150^{o}C) → communition (fine grinding) → pelleting →cooling →storage →screening and bagging.

Different grades of pellets vary in energy and ash content depending on biomass source. In use, biomass pellets provide a consistent feedstock; they are dry and clean, have a specified ash content and flow freely allowing them to be easily mechanically conveyed, for example by pneumatic conveyors.

With respect to heating value (energy available in a fuel per unit mass), grindability, combustion nature, storage, transport and handling, biomass pellets are in many cases a superior fuel. In particular, they have a heating value of about 16-19 GJ/t and an energy bulk density of 7.8-10.5 GJ/m^3, depending on the moisture content (Colley et al., 2006). Several studies have reported that the durability and strength of densified biomass increase with increasing moisture content until an optimum is reached (Kaliyan and Morey, 2009). Optimum moisture content of the feedstock is required to produce stable and durable pellets. The optimum moisture content for biomass to be pelletized is usually in the range of 8–12%. Colley et al. (2006) studied the effects of moisture content on the physical characteristics of switchgrass pellets and found that pellets with 8.6% (wet basis) moisture content had the highest durability (95.9%). The low moisture content also makes them less vulnerable to biological degradation caused by fungal growth and microbial activity so that periods of storage can be longer. Using a larger hammer mill screen size (6.5 mm instead of 3.2 mm) for communition resulted in higher pellet durability values, and use of a thicker die (44.5 mm instead of 31.8 mm die thickness) resulted in a significant increase to pellet durability for wheat straw pellets, corn stover pellets, and sorghum stalk pellets.

Biomass pellets offer many more attractive properties in comparison to untreated biomass, e.g. biomass pellets are easier to grind than untreated biomass. As pelletisation mainly consists of physical operations, feedstock quality is crucial to achieving the desired pellet quality. However, quality consistency is difficult to achieve because of the wide range of quality variables within the range of biomass feedstocks. For example, there are differences between herbaceous grasses and SRCs, among the different herbaceous grasses, and between different parts of energy crops. Moreover, climatic and seasonal variations affect feedstock properties, as well as the length of the biomass storage period and the type of storage. Improving pellet durability should be a major research and development priority for successful commercialization. Table 2.8 presents typical pellet specification; comparison of this table to Table 2.1 suggests that delayed harvesting strategy alone may not be adequate in meeting the quality standards of biomass pellets. Thus, alternative techniques/procedures may be required to improve on biomass quality for the thermochemical conversion platform.

Table 2.8: Typical pellet specification

Parameter	Values
Bulk Density	650 kg/m^3 (minimum)
Diameter (D)	4mm ≤D≥and 10 mm
Length	Less than 4 times the diameter
Moisture content	<10%
Ash content	<0.5%
Total sulphur content	<0.08%
Chlorine content	<0.03%
Nitrogen content	<0.30%
Net calorific value	>17.0 MJ/kg
Fines (% less than 3mm)	<0.8%
Mechanical durability	≥97.5% after testing

Source:
http://www.uk.remeha.com/fileadmin/user_upload/Professional_Site_UK/Technical_Specifications/Generic_Wood_Pellet_Specification.pdf

The strengths and weaknesses of pelletisation technology are summarized below:

Strengths of pelletisation technology

- Very simple technology.
- Commercially available
- Most of energy in feedstock is retained in product.
- Products can be used as an energy carrier – as pellets and briquettes that are easier to handle and transport than biomass
- Small local units can provide feed for large centralized conversion plants (either for heat/power and/or for biofuels)
- Higher energy density compared to undensified biomass.
- Pellets and briquettes are uniform physically – can be conveyed mechanically.
- Product is safer to handle than bio-oil.
- Higher combustion and gasification efficiencies

Weaknesses of pelletisation technology

- Non sawdust feedstock must be milled before it can be pelletized/
- Lower energy density compared to torrefied biomass and bio-oil.
- Pellets/briquettes can absorb moisture and can be subject to biological degradation, and therefore must be under cover in bunkers or silos.
- Potential for spontaneous combustion.
- Trace elements retained in pellets

Pellet industry in Canada

Pelletizing is the only established densification technology in Canada. There are 26 pellet plants operating in Canada: 8 in British Columbia (BC), 3 in Alberta, 1 in Manitoba, 4 in Ontario, 6 in Quebec, and 4 in the Maritimes. The dominant producer is ***Pinnacle Pellet*** which operates four plants in BC. BC and Nova Scotia plants sell primarily to Europe CHP plants, while Ontario and New Brunswick plants sell primarily to Eastern US.

During the past four years, the global pellets market has experienced a dramatic increase. Global production went from almost 8 million tons per year1 in 2007 to more than 13 million tons in 2009, of which European countries consumed more than 8 million tons. North America produced about 7 million tons in 2009, of which almost 5 million tons were intended for exports to Europe. Leading countries in the consumption of pellets in Europe are Sweden, Austria and Finland, while Germany, France and Italy are experiencing the largest market growth in both capacity and consumption of pellets. Russia is also increasing its production capacity and may become a key player for exports in the near future. In addition, countries such as Denmark, Belgium and Norway are experiencing the most significant increase of the region in pellet consumption. According to the European Biomass Association, it is expected that Europe will reach a consumption of 50 million tons per year by 2020 compared with 8 million tons per year in 2009. Regardless of increased production and consumption, European countries will have a lack of production capacity to satisfy the internal demand, mainly due to the scarce availability of sustainable sources of raw material in the EU. With an increasing demand from several European countries, and few exporters besides Canada and Germany, U.S. producers are finding a growing market that literally exploded, increasing from 2002 through 2006 by more than 200 percent. Despite this large increase in production, most pellets manufactured in the U.S. were intended for domestic consumption. Canada has dedicated more than 80 percent of its production for the export market, mainly to European countries, and is the largest exporter of wood pellets in the world. With the opening of several new facilities in the Southern U.S, the capacity for exports has expanded and European countries with demand for pellets, such as Sweden, Italy, Denmark and Norway, may take advantage of their better prices, faster shipping, and a steady availability and supply of pellets from these U.S. facilities. These countries may switch from their traditional Canadian supplier, depending on delivered prices and long-term supply agreements. The market for other continents, excluding North America and Europe remain marginal, with combined production of only 0.3 million tons per year. South America, Africa and Asia are far behind in the race for market share and positioning in the pellet market. These players must not be underestimated, however, especially countries such as Brazil. With the availability of raw material, and well-established wood and paper industry, it will be a matter of time for Brazil to become a key player in the wood pellets market.

Southern U.S has the ability to supply pellets for the European market at a competitive price because of enhanced production capacity due to a sustainable wood source from plantations. In addition, it may become a better alternative for European buyers than Canada, because of the locations of important ports, better road infrastructure and year-round harvesting. U.S. producers can achieve long-term agreements with European customers because of the increased demand for pellets, and the lack of resources (production capacity and raw material availability) to internally satisfy the demand.

2.2.2. 3. Extrusion briquetting

Briquetting is accomplished by compacting biomass material using a piston press or a roller press, sometimes in the presence of a binder material. Alternatively, a screw extrusion can be used whereby biomass is extruded by a screw through a heated die.

Briquettes can be produced with high or low pressure and can undergo mechanical or thermal treatment according to the characteristics of the processed material, the binder used and the desired end product. The briquetting units shape fine materials into larger forms of varied shapes, sizes and volumes (from a few cc up to 600 cc and more); these characteristics are defined according to the product end use. Like pellets, briquettes have very high specific density and bulk density compared to loose biomass, and compared to fire wood or loose biomass, briquettes give much higher boiler efficiency because of low moisture and higher density (Winkler, 2010). Any of the selected biomass crops in this review can be densified by briquetting, and both briquettes and pellets can be made of the same materials. It must however be noted that biomass briquettes are primarily made from the agricultural waste, forest waste and industrial waste. Examples of such wastes include rice husk, coffee husk, coir pitch, jute sticks, sugarcane bagasse, peanut shell, mustard stalks, cotton stalks, sawdust, wood chips, bamboo dust, tobacco waste, tea waste, paddy straw, wheat straw, sunflower stalk, soybean husk, and veneer Residues.

The similarities and differences between pellets and briquettes are summarized below:

Similarities

- The heating value (HHV) is the same,
- Energy content of 1 ton (2,000 lbs.) of briquettes or pellets is equal to approximately 120 gallons of fuel oil

- Ash content is the same for a given material
- For the tested pellets and briquettes no relation between durability and particle density was found (**Temmerman et al.,2006)**
- Pellets and briquettes quality can vary according to feedstock source.

Differences

- The briquetting process is more reliable and repeatable than pelleting
- Briquetting is more tolerant to different moisture levels than pelleting
- The briquetting process is more energy efficient than pelleting
- Briquetting requires less pre-processing of the raw material (less grinding and drying)
- Larger size makes briquettes suitable for different combustion equipment than for pellets
- Briquettes will not feed in pellet stoves but many boilers and multi-fuel biomass combustion equipment can handle them well

Biomass pellet machine

Biomass briquette machine

Examples of pellets and briquettes from individual energy crops

In a study conducted in Sweden, it was reported that pre-compaction of the reed canary grass (RCG) biomass raw material was an efficient method for avoiding uneven pellet production (Sylvia Larsson, 2008). RCG pellets showed a negative correlation between moisture content and pellet bulk density and a moisture content optimum for pellet durability. This is in line with previous studies on a range of straw materials. Fuel pellets and briquettes from Miscanthus are reported to last up to 3 times longer than conventional wood fuel logs (Evans, 2008). The natural binding properties for making pellets and briquettes from switchgrass appear to be lacking, and improving their durability is becoming a major area of research and development priority for successful commercialization. Lighter color pellets and briquettes have a better grade than the darker colored ones.

2.2.2.4. Pucks

In appearance, pucks are similar to hockey pucks. Biomass pucks are produced using

a briquetter. Pucks and briquette are of the same diameter but pucks are shorter in length. They are resilient to moisture and have a similar density as pellets, with the advantage that they require lower production cost compared to costs involved in pelletization. Both pucks and briquettes have been used in power generation facilities, greenhouses, schools, and even some residential settings.

2.2.2.5. Cubes

Cubes are large size pellets, but are less dense than pellets. The process of making

cubes involves compressing chopped biomass with heavy press wheel, followed by forcing the biomass through dies to produce cubes. Cube sizes range from 13-38mm in cross-section, and their length range from 25-102mm.

Appendices A1 and A2 provide more detailed information on densification machinery and/or equipment, their countries of origin and Websites links.

2.2.3. Processing Technologies

2.2.3.1. Biomass Torrefaction

Torrefaction is a technology that involves the thermal treatment of biomass to produce a solid product ("bio-coal"), and serves to improve the properties of biomass in relation to thermochemical processing techniques for energy generation such as combustion, co-combustion with coal or gasification. Torrefaction is similar in concept to pyrolysis but occurs at less severe conditions. Torrefied biomass is produced by roasting the biomass at about 250-300°C for about 30 minutes in the absence of air or oxygen to produce bio-coal. The bio-coal (also called "bio-char") can then be pelletized or briquetted to overcome the low bulk density of unpelletized torrefied biomass. The torrefaction process requires little energy input since some of the volatile gases liberated during heating are combusted, generating 80% of the heat required for torrefaction.

Pelletized torrefied biomass results in a product with stable moisture content of about 3%, reduction in mass by about 30%, a retention of 90% of the original energy content, an energy content of about 20.7 GJ/t, an energy bulk density of 14.9-18.4 GJ/m^3, and removal of smoke producing agents. Unlike biomass pellet, torrified biomass is hydrophobic and hence less subject to biological degradation during storage outdoors (http://www.techtp.com). Torrefied biomass is highly friable and, compared to wood chips and biomass pellets, can be more easily ground into a powder making it a highly suitable feedstock for co-firing with coal. However, torrefaction does not address the issues related to biomass chemical properties such as ash slagging, fouling, sintering and corrosion caused by Na and K salts. *Hemicellulose*, the most thermally unstable of the three polymeric constituents of biomass is extensively *devolatalized* and *carbonized* during the torrefaction process. Some mass loss also occurs due to the decomposition of some of the lignin which is thermally more stable than hemicellulose. The loss of the hemicellulose matrix breaks the tenacious nature of biomass making it less fibrous and more friable (i.e. more similar to coal physically). Torrefaction also drives off relatively more oxygen and hydrogen compared to carbon. Oxygen is driven off in water, organic reaction products such as acetic acid and evolved gases such as carbon dioxide and carbon monoxide. The change in the C/H and C/O ratios during torrefaction is illustrated in the *Van Krevelen diagram* (a graphical-statistical method that cross-plots Oxygen: Carbon and Hydrogen: Carbon ratios of fuels (**Figure 2.2**).

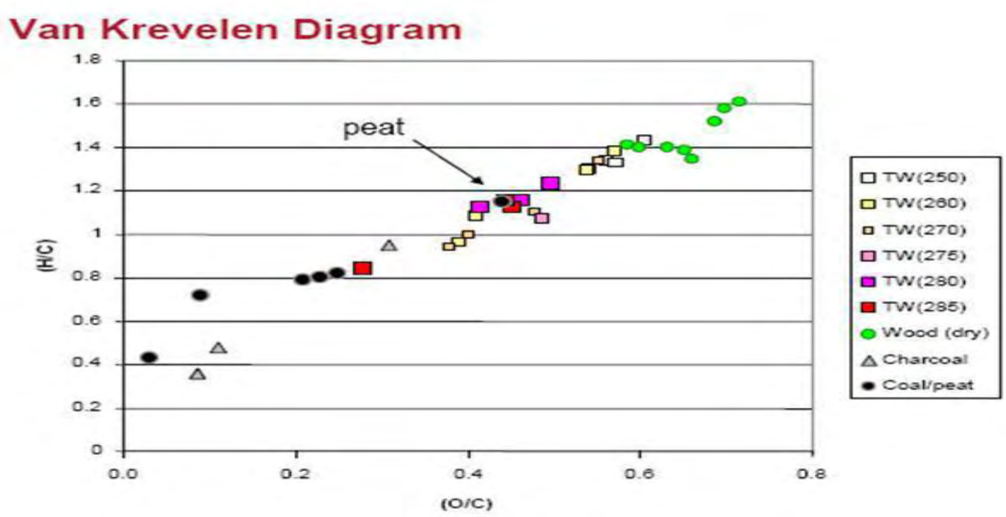


Figure 2.2 H:C and O:C ratio change as a result of torrefaction (Boerrigter, 2006)
TW=torrefied wood at different temperatures (200°C, 250°C, 275°C, 280°C and 285°C).

Compared to wood, torrefied biomass has less oxygen and less hydrogen making it closer in nature to peat and resulting in an increase in calorific value. The resulting torrefied product properties are therefore "moved" away from biomass and towards coal. Mass and energy from the biomass is largely preserved in the solid product (0.65-0.70 mass yield, 0.9 net energy yield). The losses in oxygen and hydrogen result in an increase in heating value from about 17-19 MJ/kg to between 19 and 23 MJ/kg, depending on reaction conditions. During torrefaction biomass undergoes changes in physical and chemical properties. Current knowledge indicates that torrefaction mass yield and the extent to which oxygen and hydrogen are driven out of biomass during the torrefaction process are dependent upon the type of biomass, reaction time and reaction temperature.

Lab scale research by Zanzi et al. (2007) reports that woody biomass returned higher yields of solid products compared to Miscanthus by up to 4.5% at low torrefaction temperatures (230°C) and 11% at higher temperatures (280°C) (Zanzi et al., 2007). Increasing the reaction temperature was shown to increase the amount of carbon relative to the amounts of hydrogen and oxygen – losses of hydrogen and oxygen are due to the formation of water, carbon monoxide and carbon dioxide during the torrefaction process as noted above earlier. As a result, H:C and O:C atomic ratios decrease with temperature as illustrated by the Van Krevelen diagram (see Fig. 2.2.). These differences are reported to be accounted for by differences in hemicellulose content (Boerrigter et al., 2006).

One of the advantages of torrefaction is that it can convert biomass feedstocks which have non-uniform qualities into more uniform materials. The torrefaction process thus serves as a pre-conditioning process, eliminating the need for energy conversion systems to include inefficient and expensive methods to handle feedstock variability. This is an added advantage since issues concerning feedstock handling and transfer are frequently among the biggest obstacles to effective conversion and use of biomass feedstocks.

Table 2.9. Physical Properties of Torrefied Pellets (**Mitchell et al. 2007; Boerrigter 2006)**

	WC[1]	TW	WP	PTB	BIO-OIL
Moisture content (%)	35	3	7-10	1-5	5
Calorific value as received (MJ/kg)	10.5	19.9	15.6-16.2	19.9-21.8	16-19 (22.2 dry basis)
Bulk density (kg/m³)	550	230	500-650	750-850	1,200
Energy bulk density (GJ/m³)	0.8	4.6	7.8-10.5	14.9-18.4	19.0
Propensity to form dust	moderate	high	limited	limited	Nil
Hydroscopic nature	Absorbs water	Hydrophobic	Swells, absorbs water	Poor swelling, hydrophobic	n/a
Storage stability	Gets mouldy, dry matter loss	Stable	Deteriorates, gets mouldy	Stable	Viscosity increases with time
Handling characteristics	baseline	baseline	better	better	Liquid (excellent)

[1]**WC**=Wood chips; **TW**=Torrefied wood; **WP**=Wood pellets; **PTB**=Pelletized torrefied biomass.

As an example, Table 2.9 provides some physical properties of torrified and un-torrified pellets derived from wood. The calorific value, bulk density and energy bulk density of torrified pellets increase with both time and temperature of torrefaction, while the yield on a weight basis decreases. By pelletizing the torrefied biomass, energy bulk density is increased from 15 to 18.5 GJ/m³ compared to 8 to 11 GJ/m³ for wood pellets. This additional processing step makes torrefied biomass highly suitable for use in place of wood pellets. In poplar and willow, a 17% increase in energy bulk density of torrified pellets was reported (from 17.7 to 20.7 MJ/kg on a dry weight basis) (Bergman, 2005; Bergman and Kiel, 2005). Figure 2.3 illustrates changes in biomass properties as a result of densification processes: torrefication increases both bulk density and heating value of pellets whilst the moisture content is decreased.

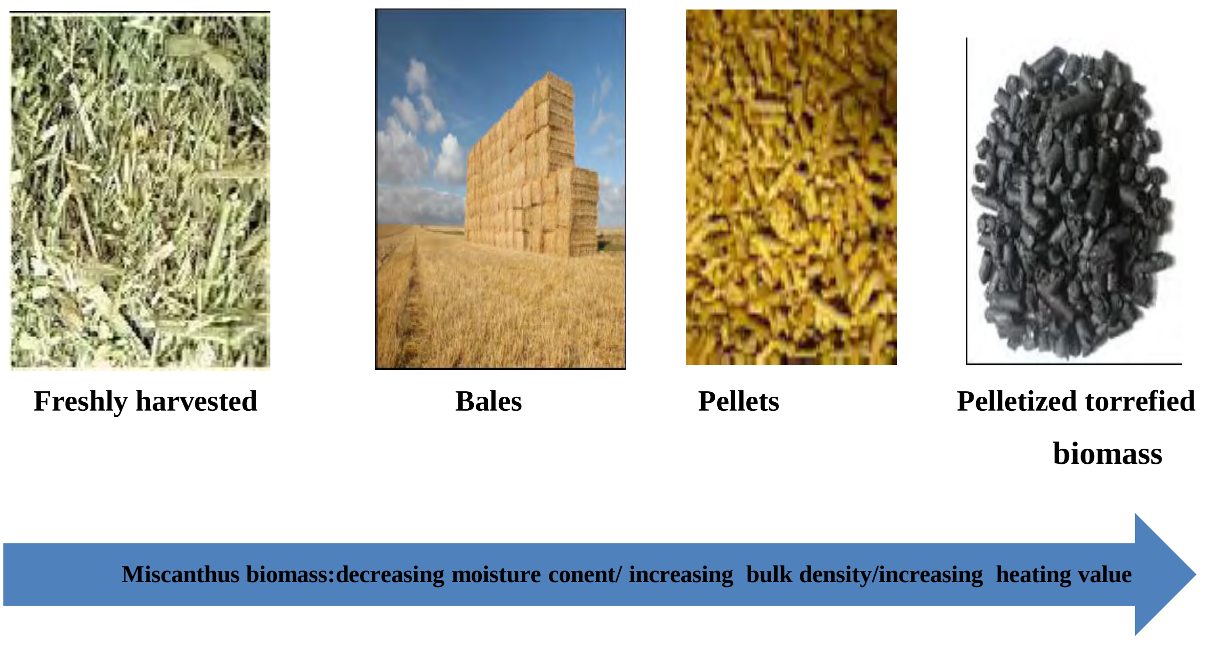


Figure 2.3. Changes in biomass properties as a result of densification processes

As all biomass contain lignocellulose, a wide variety of biomass sources can be torrefied while at the same time yielding similar products. However, as their polymeric structures differ, mass and energy yields will be different. Grass for example will undergo more significant mass change during torrefaction due to the high levels of lipids and waxes in grass which are driven off by the torrefaction process (Bergman, 2005). Research is ongoing at the University of Guelph and elsewhere to determine the impact of torrefaction on the physical properties of diverse biomass sources.

Uses of torrefied biomass

Torrefied biomass can be used in a variety of combustion and gasification applications. For example, torrefied pellets may be used for wood pellet replacement, barbeque substitutes, biochar, space heating (commercial and domestic), for co-firing in large generators and distributors with coal-fired power plants, industrial power production, and direct industrial use (e.g. Cement works, Iron and Steel foundries, Chemical and Paper manufacturers and large engineering plants). The picture above provides a typical portable torrefaction unit. The strengths and weaknesses of the torrefaction technology may be summarized as follows:

Strengths

- Simple technology
- Converts biomass into an energy carrier either bio-coal or torrefied-pellets)
- Most of energy in feedstock is retained in product.
- Product can be used as an energy carrier – as pellets, easier to handle and transport than biomass
- Small local units can provide feed for large centralized conversion plant
- Product is friable, low in moisture
- Oxygen content is reduced compared to wood.
- Higher energy density compared to wood pellets.
- Product is stable and hydrophobic – can be stored outdoors.
- Product is not susceptible to biological degradation.
- Product is safer to handle than bio-oil.
- Higher combustion and gasification efficiencies compared to wood chips and pellets.
- Process can be applied to a wide range of biomass and wastes (including plastics).

Weaknesses

- Technology is more complex than pelletisation but less complex than pyrolysis.
- Limited research and development (R&D) base in Canada
- Extremely limited commercial experience and proposed commercial units are relatively small capacity
- No large scale testing completed
- Lack of technology suppliers

- Loss of conversion efficiency for BTL
- Lower energy density compared to bio-oil
  Product is a solid.

2.2.3.2 Biomass Pyrolysis

Pyrolysis is a process in which dried and comminuted (finely ground) organic materials are heated to temperatures between 350-500°C in the absence of oxygen and air. If the material is heated at temperatures up to 350-500°C for extended period of time (typically 0.5 to 2 hours), the process is called *'slow pyrolysis*; if the processing is rapid at temperatures up to 450-500°C for only 1-2 seconds, it is referred to as *'fast pyrolysis'*. In slow pyrolysis, the main product is a solid 'charcoal' which retains 60-70% of the original energy from the raw materials. Thus, slow pyrolysis is similar to torrefaction. In fast pyrolysis, the process yields up to 75% 'bio-oil' and 10-15% charcoal and a gas. The processes involved in fast pyrolysis are summarized in Figure 2.4.

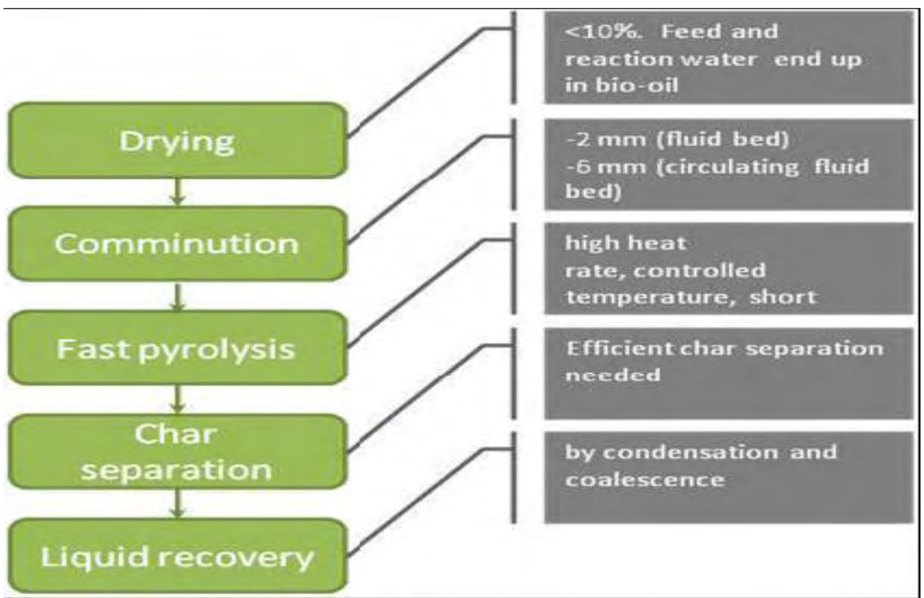


Figure 2.4. Pyrolysis Process Steps (Adapted from Bridgewater, 2002)

The **bio-oil** is the only densified product that can be directly upgraded to transport fuels in an oil refinery. Bio-oil is a dark brown, mobile liquid with a characteristic pungent smoky aroma which has a heating value of about 17.5 GJ/t. The bio-oil can potentially be used directly as a fuel in static engines, gas turbines and/or boilers and furnaces. It can also be converted to 'syngas' from which advanced biofuels can be produced or it may potentially be upgraded to oil refinery products, ranging from *C1 permanent gases* (i.e. methane) up to and including products in the diesel range, in an oil refinery. The gas by-product can be used within the process to provide process heat and/or electricity. Bio-char derived from slow pyrolysis and torrefaction have similar characteristics. Bio-char originating from fast pyrolysis can be used within the process to provide process energy, or used as a soil conditioner or ground to a fine powder and mixed back in with the bio-oil product to make slurry oil for future gasification at a biorefinery. Other products formed include organic vapours containing three groups of materials: water, acids and aldehydes and a lignin derived heavy oil. The lignin-derived heavy oil has most potential for use as a fuel so high lignin feedstocks are potentially more suitable feedstocks for pyrolysis (Chiaramonti et al., 2005)**.** After cooling and condensation, the organic vapours form a dark brown mobile liquid with a characteristic pungent smoky aroma which has a heating value about half that of conventional fuel oil. Typically, 70-75% dry weight of the feedstock is converted into oil with the yield increasing with increasing feedstock volatiles content and decreasing with increasing feedstock ash content (Chiaramonti et al., 2005). The gas by-product can be used within the process to provide process heat and/or electricity. So far, feedstocks which have been tested include wood (e.g. pine, spruce, and larch), sugar cane bagasse, switch grass and straw.

Among many others, the main concerns with utilization of pyrolysis liquid relate to a number of technical issues including: high acidity (typically pH 2.5) and the large number of different chemicals contained in the bio-oil. A summary of the strengths and weaknesses of pyrolysis include:

Strengths of pyrolysis

- Simple technology but more complex than torrefaction and Pelletization;
- Converts biomass into a dense energy carrier (either bio-oil or oil/char slurry);
- Energy carrier easier to handle and transport than biomass;
- Small local units can provide feed for large centralized conversion plant.

Weaknesses of pyrolysis

- Finely ground and low moisture content biomass feed required;
- Low quality bio-oil product is acidic and unstable;
- Bio-oil difficult to upgrade directly;

- Loss of conversion efficiency for BTL (~7 t of dry biomass per t of synthetic diesel needed).

2.4. Hydrothermal Upgrading (HTU)

Hydrothermal upgrading is a developmental *liquefaction technology* in which ***wet biomass*** is reacted with liquid water at elevated temperature and pressure to produce a high energy density 'biocrude'. The biocrude can potentially be used for co-firing in coal fired power stations or converted to hydrocarbon fuels (i.e. diesel). It is the least developed of the "densification" technologies and produces a product with the most limited range of applications. However, it is the only technology to be able to produce a liquid biomass directly from a wet feedstock including the biological fraction of municipal solid wastes. The HTU process "pressure cooks" biomass at 300-350°C, 120-180 bar pressure and 5-20 minutes residence time in liquid water. The resulting biocrude has an energy density of 30-35 GJ/t and a melting point of 80°C. A wide range of feedstocks are reported to be suitable for hydrothermal upgrading; these include wood, agricultural residues and the biological fraction of municipal solid wastes. Our five selected plant species may be used for HTU; currently however, there are no reports on this in Canada. A key feature of this process is that the feedstock can be processed wet (up to 80 wt %). Figure 2.5 summarizes the HTU process steps (Goudriaan, 2008).

Strengths of HTU

- Simple technology although more complex than torrefaction and pelletisation.
- Converts biomass into a dense energy carrier (biocrude)
- Energy carrier easier to handle and transport than biomass – could be used as biorefinery feedstock.
- Wastes are cleaned water and flue gases
- Wet biomass can be processed (up to 80 wt.%)
- Biological fraction of MSW processing proven at pilot scale

Weaknesses of HTU

- Few developers
- Not demonstrated above pilot scale

- Product is solid below 80°C – difficult to use except in co-firing applications or for upgrading
- Loss of conversion efficiency if used as a remote biomass pretreatment step for a biorefinery.

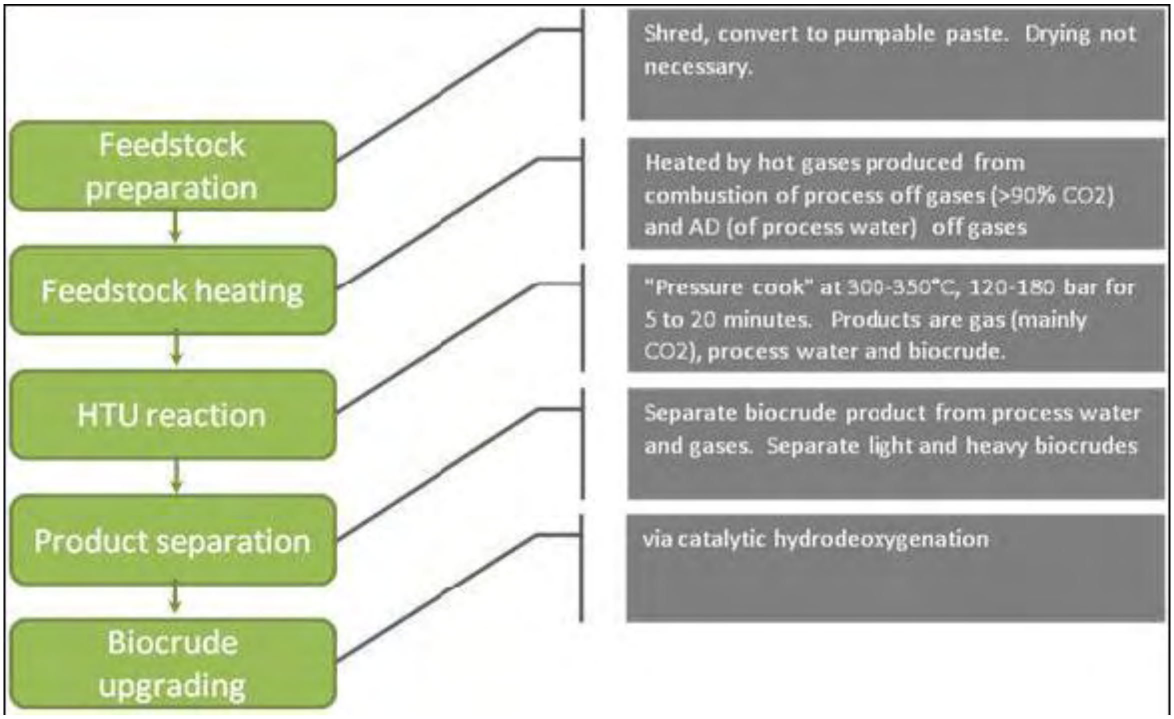


Figure 2.5. HTU process steps (Goudriaan, 2008)

A summary of the major densification and processing technologies and products discussed in this review is presented in figure 2.6. It is however important to note that of the “densification” and processing technologies described above, only mechanical densification, particularly biomass pelletization, is currently commercialized in Canada.

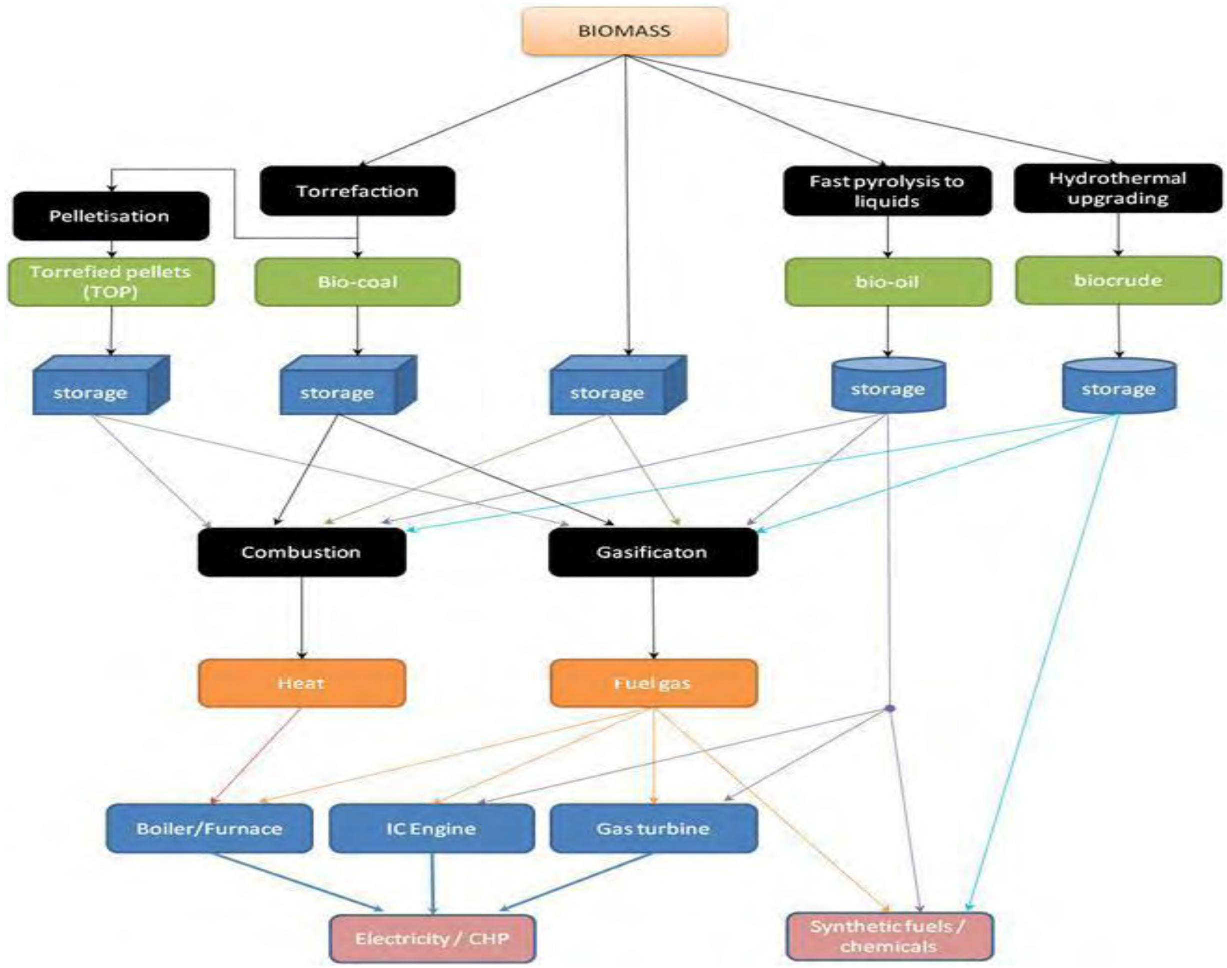


Figure 2.6. Products from Thermal Biomass Conversion (Adapted from Bridgwater, 2005)

2.6. Issues on improving biomass quality for combustion

High biomass moisture content

Except for torrefaction and HTU, feedstock moisture content must ideally be brought down to about 10-15% before thermochemical processing (Evans, 2008). Only materials of suitable moisture content should be compressed into pellet/briquette forms. Accurately controlling moisture to the ideal percentage can affect pellet quality, pellet mill productivity and energy input. In a 2010 study conducted by the ***PetHeat Company*** in England, the three parameters changed according to the moisture content (Pellet Production Solutions, 2010: http://www.Pelheat.com)**.** The study conducted trials on the same raw biomass material with different moisture contents ranging from 12% up to 16% (Figure 2.7). Pellet quality, measured as the *Pellet Durability Index*

(PDI), refers to the density and compression of the pellet. A higher number for the PDI means a better quality pellet. The *Specific Energy Use* refers to how much energy the pellet mill is consuming to produce one ton of pellets; a lower figure implies reduced production costs. The study indicated a slight improvement in production rate with an increase from 12% to 13% moisture content. There is again a slight increase from 13% to 14%. However, the graph also shows that increasing moisture content from 14% to 15% has a profound effect on reducing productivity by roughly 25%. This decline continues from 15% up to 16%. Thus, the ideal for this raw material is clearly 14%, and moving from 14% up to 16% moisture content has seen a massive 75% reduction in productivity.

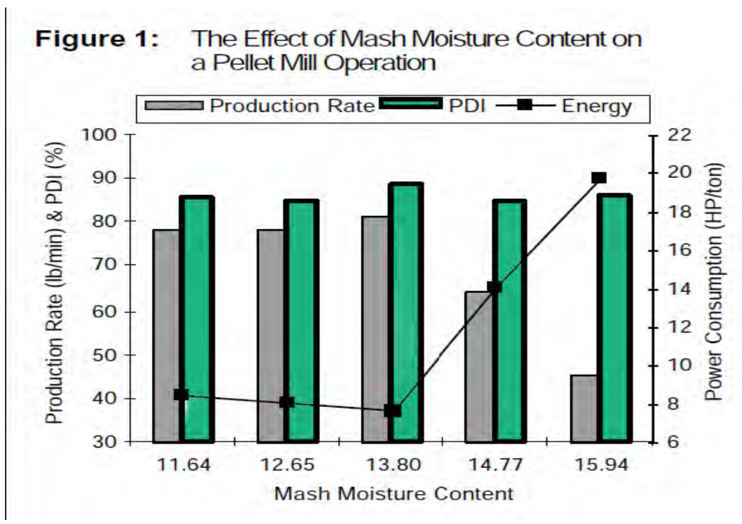


Figure 2.7. The effect of moisture content on pellet mill operation (http://www.Pelheat.com)**.**

An increase from 12% up to 13% in moisture content sees a slight reduction in pellet quality (i.e. PDI). However, moisture content increment from 13% to 14% indicates an increase in PDI and also clearly produced the highest quality pellet in the test. From 14% to 15% and then 16% shows a slight reduction in pellet quality.

The important thing to note from the graph is the relationship between productivity and pellet quality: 14% moisture content is ideal for this particular biomass type in both maximum productivity and pellet quality. One of the most significant effects due to a change in moisture content is in pellet mill energy consumption. From 12% to 13% moisture content, there is a drop in energy demand; energy consumption is at its lowest from 13% to 14%. However moving from 14% up to 15% results in a massive increase in energy consumption and likewise from 15% to 16%; this also comes with a reduction in production rate and pellet quality.

For torrefaction, high moisture content is reported to be beneficial since evoluted torrefaction gases are used to dry the incoming feedstock. It has been reported that at about 57% moisture content for wood, the energy provided by the torrefaction gases is sufficient for feedstock drying – referred to as *autothermal operation* (Bergman and Kiel, 2005).

Alkali metal content

The quality of plant biomass quality can also be upgraded through cultural management practices to reduce the chlorine and the alkali metal (i.e. Na, K, Mg, P and Ca) content of biomass. Densification of the biomass material (e.g. pellet) does not *per se* reduce the concentrations of these elements. As outlined in chapter 1, delayed harvesting, for example, has been shown to leach out most of the elements/plant nutrients (Cl, K, Na and Ca) considered problematic.

Particulate Matter (PM): health issue

Particulate matter and partially oxidized organic compounds are known to be important indicators of air quality and also have significant impact on human health (Nikolaou, 1984; Swartz, 1995; Mccrillis, 1992). For example, an Italian study has established a relationship between PM emission and biomass characteristics related to the combustion of biomasses with different properties (Pedretti et al., 2010). Figure 2.8 shows the effect of ash content on PM levels of four pellet sources; high ash content resulted in high PM. High PM could also originate from combustion operations such as inadequate mixing between combustion air and biofuel, low combustion temperatures and short residence times of the combustion gases at higher temperatures (Van Loo, 2008). Since ash content is dependent on biomass source apart from the combustion operations, choice of biomass source becomes very important. In this review, we noted earlier that except for Miscanthus, the ash content of the other four biomass types is more than 2.4%, indicating that biofuels from these sources could be producing high levels of PM during combustion (see Tables 2.3-2.7). The study by Pedretti et al. (2010) suggests the development and adoption of technical standards as one of the most effective ways of reducing PM production, allowing a comparison between biomass producers, manufacturers' devices and monitoring agencies. Biomass combustion systems can also be improved by developing codes and regulations.

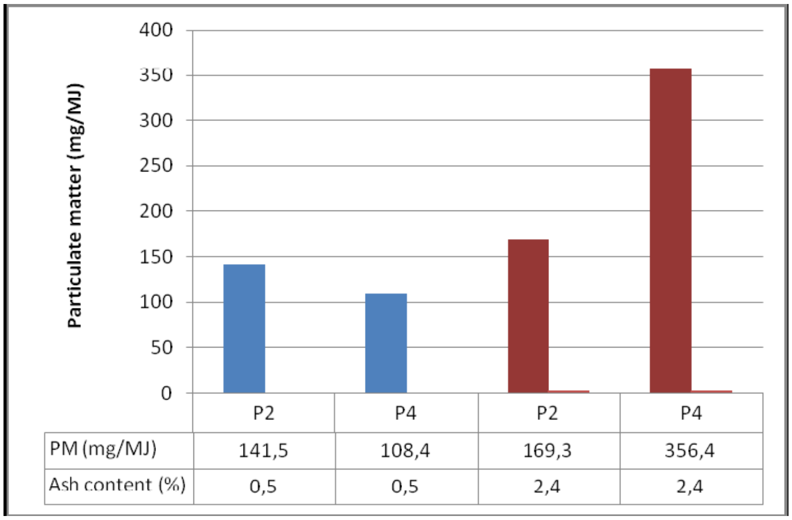


Figure 2.8. Particulate Matter (PM) level for different biomasses and combustion conditions in the pellet stove **(**Pedretti et al., 2010)

High Ash content

The ash content of biomass affects both the handling and processing costs of the overall, biomass energy conversion cost. Dependent on the magnitude of the ash content, the available energy of the fuel is reduced proportionately (McKendry, 2002). As discussed earlier, in a thermo-chemical conversion process, the chemical composition of the ash can present significant operational problems. This is especially true for combustion processes, where the ash can react to form a slag (Pambudi, 2011).

Biomass “densification” technologies have the potential to add value to agricultural businesses in Canada. Pelletisation, torrefaction and liquefaction by pyrolysis and hydrothermal upgrading have each been applied to a range of wastes and biomass sources such as municipal solid wastes, agricultural biomass, forestry wastes, and food processing wastes. However, of the available “densification” technologies, only biomass pelletisation is currently commercial in Canada. Issues associated with high contents of moisture, ash, alkali metals and chlorine, and particulate matter of some biomass sources need to be addressed for some of the densification technologies.

Chapter 3. Environmental impacts of producing energy crops

Although the production of dedicated energy crops for developing bioenergy is gaining global popularity in recent years, the benefits and risks of this initiative on soil and environmental quality have not been fully documented. The potential benefits or costs to the environment, and the sustainability of different bioenergy crop types need to be assessed. This chapter is devoted to reviewing the literature on the impact of growing energy crops on soil and environmental quality in terms of life cycle analysis (carbon footprint, water footprint, energy balances and carbon offsets), soil erosion control, phytoremediation and biodiversity. Relevant data and information were obtained from available published work, and from personal communication with experts in this field.

3.1. Life cycle assessment (LCA) of producing energy crops

Life cycle assessment (LCA, also known as *life cycle analysis, ecobalance, and cradle-to-grave analysis*) is a technique to assess each and every impact associated with all stages of a process from cradle-to-grave (i.e., from raw materials through processing/manufacture, distribution, use, repair and maintenance, and disposal or recycling. LCA is intended to provide systematic inventory and impact assessments of the environmental implications of a product, a process or a project throughout its life cycle (ISO, 2006a). A comprehensive LCA for a biofuel would be derived from three primary sources: the *agricultural sector* (from planting to harvest and storage), *the industrial sector* (densification and processing of biomass into biofuel), and the *distribution sector* (transportation and distribution). With respect to thermochemical energy, LCA assess the total finite primary energy consumption, total greenhouse gas (GHG) emissions and the total acidifying gas emissions of heat generation (Lewandowski and Heinz, 2007) from an energy crop. ISO 14040 specifies four phases/steps in LCA: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. The *goal and scope* of an LCA is the ground plan of the LCA study; it constitutes the first phase of the LCA, stating the aim of an intended LCA study, the functional units of the system alternatives considered and the breadth and depth of the intended study in relation to its aims. The *Inventory analysis* is concerned with the collection and analysis of all necessary data to meet the goals of the defined study; this step is considered to be the most time and resource consuming phase of an LCA. The LCA *impact* *assessment* is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. The *interpretation* phase describes the steps involved in summarizing and discussing steps/phases 2 and 3 (i.e. inventory analysis and impact assessment) in accordance with the goal and scope definition.

In the context of energy crop production, the analysis is limited to only on-farm agronomic activities (from planting to harvesting and storage) involved in the production of each of our five selected energy crops and enables the estimation of the cumulative environmental impacts resulting from the activities. To this end, we may refer to this partial LCA as a *"process-chain-analysis (PCA)"* (Kaltschmitt, 1997), where the process refers to only farm-gate agronomic activities involved in biomass production. By including the environmental impacts throughout the production of each crop, the PCA provides a comprehensive view of the environmental aspects of the resulting biomass and a more accurate picture of the true environmental trade-offs in plant specie selection. It is meant to be particularly helpful in assessing the relative attractiveness of alternative bioenergy crop types. For example, a complete accounting of net greenhouse-gas (GHG) fluxes from Miscanthus production (perennial) compared to that of biomass sorghum (annual) is required to develop and evaluate mitigation strategies of these gases. Energy crops also provide an important option for farmers with environmental benefits such as reduction in carbon and water footprints, better water quality, reduced erosion and increased biodiversity**.** The goal of this partial LCA (i.e. PCA) review is to evaluate these environmental benefits in general terms and to indicate the net effect of growing the selected crops on energy consumption and GHG emissions, using available information from published work. A more comprehensive LCA of the selected crops (from plant cultivation to heat/electricity generation) is beyond the scope of this review, but is planned for the future.

3.1.1. Carbon footprint

A **carbon footprint** in producing energy crop biomass is a measure of the impact of the agronomic activities on the environment, particularly the emission of GHGs. It relates to the amount of GHGs produced in the manufacture and use of farm inputs and farm machinery and equipment through burning fossil fuels. It is normally expressed as CO_2e (equivalent CO_2). The following categories of on-farm energy use and GHG emissions are normally included in estimating the carbon footprint energy crop production:

1. Crop production requirements of fossil-fuel inputs that may result in CO_2 emissions (diesel, electricity, natural gas) during tillage, planting, storage and on-farm transportation
2. The direct and indirect emissions of nitrous oxide (N_2O) due to the application of N fertilizers. Direct N_2O emissions are emissions from the field on which the biomass is grown; indirect emissions are the N_2O emissions from the N that is lost via runoff and leaching (as NO_x, NH_3, NO_3) and that is emitted elsewhere.
3. The manufacturing of agricultural inputs (herbicides, fertilizers and planting material).
4. The production, repair and maintenance of agricultural machinery and vehicles.

Crop production requires fossil-fuel inputs that may result in CO_2 emissions, and impacts the fluxes of non-CO_2 greenhouse gases. The major sources of GHG fluxes associated with crop production are soil nitrous oxide (N_2O) emissions, soil carbon dioxide (CO_2) and methane (CH_4) fluxes, and CO_2 emissions associated with agricultural inputs (e.g. fertilizers and agrochemicals) and farm equipment operation (Robertson et al., 2000, Del Grosso et al., 2001a, West and Marland, 2002). Crop systems emit N_2O directly, through either nitrification or denitrification in the cropped soil, and also indirectly, when N is lost from the cropped soil as some form other than N_2O (i.e. NO_x, NH_3, NO_3) and later converted to N_2O off the farm. Independent of GHG accounting, NO_3 leaching is also important from a water-quality perspective because it contributes to aquatic eutrophication and can pose a health risk to humans (Adler et al., 2007).

Bioenergy cropping systems vary with respect to length of the plant life cycle, yields, feedstock conversion efficiencies, nutrient demand, soil carbon inputs, nitrogen losses, and other characteristics, all impacting management operations (Adler et al., 2007). These factors affect the magnitude of the components contributing to net GHG flux and N loss vectors. N_2O emissions and NO_3 leaching vary with amount of N fertilizer applied and the integration of rainfall, soil temperature and texture. As an example, Miscanthus is well-suited to low requirements for nutrients as a result of efficient recycling of nutrients from above ground biomass to below ground rhizomes in the autumn and winter with harvest of above ground biomass in late winter or early spring. As such, fertilization of Miscanthus stands is very low. Soil organic carbon (SOC) sequestration is affected by crop management decisions, which impact the quantity and quality of crop residue added to the soil and rate of decomposition (Paustian et al., 2000, Jarescki and Lal, 2003). Crops also have different requirements for farm machinery inputs from crop planting, soil tillage, fertilizer and pesticide application, and harvest (West and Marland, 2002). Several studies have evaluated the energy balance (Marland and Turhollow, 1991; Shapouri et al., 2002; Farrel et al., 2006) and GHG fluxes (Sheehan et al. 1998, 2004; McLaughlin et al., 2002; Heller et al., 2003; Spath and Mann, 2004; Updegraff et al., 2004; Kim and Dale, 2005) of specific bioenergy crops. Net GHG fluxes from crop production are normally evaluated through energy generation or fuel use. With respect to the five plant species in this study, sources of GHG fluxes would include carbon dioxide equivalent (CO_2e) of direct and indirect N_2O emissions, CO_2 emission from manufacture of chemical inputs, and fuel used by agricultural machinery for tillage, planting, fertilizer and pesticide application, harvesting, and storage. Previous research reports (e.g. Westland and Marland, 2002, Lal, 2004) indicate that the energy required for farm operations varied widely depending on the type of crop and management practices (e.g. need for plant establishment and its duration), the differences being the result of frequency of farm implement use, the load the equipment is under during operation, and the required crop-specific equipment. For example, with the exception of hybrid poplar, it was reported that perennial cropping systems can have lower agricultural machinery inputs than annual systems (Adler et al., 2007). In this same study, it was reported that C emissions from tillage accounted for less than 10% in switchgrass and reed canarygrass and less than 2% in hybrid poplar, compared to 30% in corn rotations, because of tillage usage for only the first year in the perennials. Several studies have reported the importance of perennial energy crops as net GHG sinks compared to annual crops (Adler et al., 2007; Westland and Marland, 2002; Lal, 2004). Soil C storage results from changes in C inputs, tillage intensity, and residue decomposition, and soil C input from root turnover, crop residue, and live root biomass varies with crop. Although perennial grass crops (e.g. Miscanthus, reed canarygrass and switchgrass) would have larger C inputs from roots, most of the aboveground biomass are normally removed with harvest and not returned to the soil. By comparison, only about 50% or less of corn stover is removed, resulting in large soil C inputs in corn rotations from aboveground biomass. Thus, the net amount of C stored would depend on the balance between tillage frequency (higher for annuals if conventional tillage is practiced with negative impact) and the total amount of aboveground biomass left in the field after harvest (higher for annuals with positive impact). A decrease in residue decomposition due to reduced soil tillage (Paustian et al., 2000; West and Post, 2002) and reduced quality of crop residues (Heal et al., 1997) would also increase SOC. As another example, Miscanthus is well-suited to marginal lands as it has low requirements for nutrients as a result of efficient recycling of nutrients from above ground biomass to below ground rhizomes in the fall and winter with harvest of above ground biomass in late winter or early spring. In general, the perennial crop systems under Miscanthus, reed canarygrass, switchgrass, and hybrid poplar would be expected to have increased SOC through reduction/elimination of tillage and increased root biomass.

In the *"Management Guide for switchgrass production in Ontario",* Samson (2007) noted that switchgrass and other warm-season grasses could help Canada achieve major GHG emission reduction targets. He noted that, bioenergy grass pellets can reduce GHG emissions by about 90% when compared with using an equivalent amount of energy in the form of fossil fuels. A US study by Liebig et al. (2008) reported that switchgrass can produce 185 GJ/ha of energy versus 120 GJ/ha for grain corn assuming a harvested grain corn yield of 6.5 t/ha and a switchgrass yield of 10 t/ha; they also noted that 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.

The long-term C sequestration potential of soils is affected by soil properties such as texture, and some will saturate at higher SOC levels than others (Six et al., 2002). Therefore the potential long-term storage of SOC will depend on the cropping system and how it is managed, and the specific soil (Adler et al., 2007). In general, production of perennial energy crops are reported to have higher yields, greater soil C sequestration, reduced GHG emission from feedstock conversion, reduced soil N_2O emissions, and reduced GHG emissions from chemical input manufacture and agricultural machinery operation.

3.1.2. Water footprint

The *water footprint* of a crop is defined as the total volume of freshwater used to produce the crop, including its evapotranspiration (combination of soil evaporation and transpiration). Crop biomass production is intimately related to water use; thus, the production of energy crops can change the water balance of an area via changes in evapotranspiration, runoff and percolation compared to the agricultural land that is replaced (Stephens et al., 2001). Also the interception of rainfall by energy crops such as Miscanthus, switchgrass, sorghum and poplar is higher compared to annual crops Aitchison et al. (2000). As a result, the deep percolation and runoff of water from areas under perennial energy crop cultivation may be reduced compared to annual crops. This may ultimately lead to adverse hydrological impacts such as reduced aquifer recharge and stream flow that feed reservoirs, wetland and other ecosystems. In this study, we provide a general review of water use of energy crops without details of the hydrological impacts. Although related, we must distinguish between water footprint and *water use efficiency*; with respect to energy crops, water use efficiency may be defined as the dry matter (biomass) produced per water loss. Thus, although an energy crop may have high water use efficiency, its water footprint may be high. An advantage of the high water use of energy grasses is that the high water use may be employed to reduce peak flows and thereby reduce the risks of local flooding.

Most studies indicate that, because of the fast growth, large leave area and deep rooting system, the rate of evapotranspiration of energy grasses is higher compared to traditional annual crops (Zhang et al., 1999; Aitchison et al. 2000). A large leaf area implies that the foliage may intercept 20% to 30% of rainfall, which then evaporates directly from the leaves. As a result, deep percolation and runoff of water from areas under energy grass cultivation is reduced compared to annual crops. Calculations done for four sites in the UK (precipitation of approximately 650 mm) showed a decrease of the amount of *hydrological effective rainfall (HER*; defined as rainfall available for percolation plus runoff) of 50–60% compared to annual crops (Aitchison et al., 2000). The study concluded that the reduced percolation and runoff to groundwater reservoirs, streams and rivers in those areas may lead to a depletion of these water bodies. However, the Ontario environment is quite different: annual precipitation from rainfall and snow ranges between 900 and 1,000 mm and the evapotranspiration dynamics of the province may be completely different from those at the UK sites. Therefore, the impact of perennial energy crops on fresh water reservoirs would likely be more limited, and high water may not necessarily impact energy crop production negatively in the province. On the contrary, depending on the soil type and topography, the production of energy crops such as Miscanthus and switchgrass in Ontario may actually enhance water infiltration, mitigate runoff and thereby increase groundwater recharge because of the positive impact of these crops on the physical properties of the soil (e.g. enhanced water holding capacity). Long-term study in this area is warranted.

3.1.3. Energy balances (Energy return over energy invested, EROEI))

It is a well-known fact that all technologies, including biofuel options, involve the use of fossil fuels in their production and operation, resulting in associated GHG emissions (Elsayed et al., 2003). Hence, the actual benefits realized by biofuel technologies depends very much on their energy and carbon balances which indicate the magnitude of fossil fuel inputs (and related GHG emissions) relative to subsequent fossil fuel savings (and avoided GHG emissions) resulting from their use as alternatives to conventional energy sources. Energy balance describes the total amount of energy input into making a biofuel product (e.g. pellets, ethanol) compared to the energy released by burning the resulting biofuel product. An energy ratio $MJ_{produced}/MJ_{input}$ is normally used to quantify energy balance of a biofuel product (see Table 3.1.). A comprehensive LCA is normally conducted to determine whether a biofuel has favorable energy balance or not. Several studies have evaluated the energy balance of specific bioenergy crops in the production of specific biofuels (Marland and Turhollow, 1991; Shapouri et al. 2002; Farrel et al. 2006). The net energy value of a biofuel (e.g. pellet, ethanol, etc) is positive (or >1) when the energy consumed in the production of the biofuel is less than the energy content of the biofuel. To illustrate the concept of energy balance in bioenergy production, we can use the example of ethanol production from sugarcane, as reported by De Oliveira et al (2005). Energy-use associated with the production of sugarcane ethanol derives from three primary sources: the agricultural sector, the industrial sector, and the distribution sector. In the *agricultural sector*, 35.98 GJ of energy are used to plant, maintain, and harvest one hectare (10,000 m^2) of sugarcane for usable biofuel. This includes energy from numerous inputs, including nitrogen, phosphate, potassium oxide, lime, seeds, herbicides, insecticides, machinery and diesel fuel. The *industrial sector*, which includes the milling and refining sugarcane and the production of ethanol fuel, uses 3.63 GJ of energy and generates 155.57 GJ of energy per hectare of sugarcane plantation. In *terms of distribution*, one hectare of land would require 2.82 GJ of energy for successful transport and distribution. After taking all three sectors into account, the EROEI (Energy Return over Energy Invested) for sugarcane ethanol is about 8. Table 3.1. provides a summary of energy ratios of baled (pre-densified) biomass of some energy crops from a studies compiled by Rowe et al. (2009). Miscanthus provides the highest energy ratio while RCG has the lowest, indicating that Miscanthus would be best choice for energy production.

***Table 3.1. Energy ratio of energy crops (adapted from Rowe et al. (2009*).**

Fuel source	**Energy ratio $MJ_{produced}/MJ_{input}$**	**Source**
SRC willow and poplar	28.68	Matthews (2001)
Reed canary grass	20.4	Edmundo and Ulf (1993)
Miscanthus	35.86	Bullard and Metcalfe (2001)
Switchgrass	20.1	Samson et al. (1999)
Biomass sorghum	N/A	N/A

3.1.4. Carbon offset generation

A **carbon offset** is a reduction in emissions of carbon dioxide or GHGs by a process with the aim of compensating for or offsetting emissions made elsewhere. Carbon offsets are measured in metric tons of equivalent CO_2 (i.e. CO_2e, the concentration of CO_2 that would cause the same level of *radiative forcing* as a given type and concentration of GHG, e.g. methane, nitrous oxide). One carbon offset represents the reduction of one metric ton of CO_2 or its equivalent in other GHGs.

As sources of renewable energy, perennial energy crops exhibit two major mechanisms by which they can offset carbon emissions: carbon mitigation and carbon sequestration (Sartori et al., 2006; Schlamadinger and Marland, 1996; Lal *et al.*, 1999; Frank *et al.*, 2004; Volk *et al.*, 2004; Liebig *et al.*, 2005). The net benefits of replacing fossil fuels with biofuels depends on both the energy contained in the biomass and also on the energy required to grow the crop and convert it to a usable energy form **(**McLaughlin and Walsh, 1998)**.** For example, the GHG balance for Miscanthus has been found to be quite positive (Styles and Jones 2007; Lewandowski et al. 1995). Regarding carbon mitigation, energy crops are considered to be carbon neutral fuel as the carbon that is released during their combustion has been absorbed by the plants when they were growing. Thus, there is no net increase in CO_2 into the atmosphere. Furthermore, GHG emissions from energy crop cultivation will be lower than those from other agricultural activities, largely due to lower amounts of the usage of fuel, fertilizer and agrochemicals. Energy crops can also sequester carbon (C), preventing its release into the atmosphere. Carbon sequestration occurs when the inputs of C are greater than removals from harvesting and decomposition; C may be stored in soils under energy crops, in rhizomes and/or roots as well as in un-harvested stubble of energy crops. However, the rate of C sequestration depends on land-use history, soil type, plant type, harvesting cycle, and other management practices (Sartori et al., 2006). For example, although there are currently few completed long-term studies under energy crops that provide data on specific effects of management practices on SOC dynamics, some long-term studies in the Canadian prairies support the conclusions by Conant et al. (2001) that management to achieve SOC is important only in soils with an initially low initial/baseline SOC (Janzen et al., 1998).

Experiments conducted in Ireland have shown that Miscanthus can store 8.8 t C/ha in its roots and rhizomes 12 years into its life (Caslin et al., 2010). Liebig et al. (2008) also reported that land conversion to switchgrass on Conservation Reserve Program (CRP) plantings in the United

States has led to about 10.9 t C/ha being stored in the soil compared to conventional land use. Table 3.2 provides examples of reported rates of SOC sequestration under some selected energy crops.

Table 3.2. Reported rates of SOC sequestration under some selected energy crops.

Energy crop	**Location**	**Previous land use**	**C-sequestration rate (t/ha/yr)**	**References**
Poplar	Minnesota (USA)	Grassland, corn	0	Grigal & Berguson (1998)
	ND, MN, WI, IA (USA)	Tilled soil	1.6	Hansen (1993)
Switchgrass (Alamo)	TN, VA (USA)	Small grains field	0 (1.7-2.1 as root biomass inputs)	Garten & Wullschleger (1999; 2000)
Switchgrass (Cave-in-Rock)	Montreal, Quebec (Canada)	Abandoned agric. field	0; 3.5 (on sites with manure input)	Zan et al. (2001)
Miscanthus	U.K.	NA	0.5	Bullard & Metcalfe (2000)

In an example provided by a study in the UK, 100 tonnes of Miscanthus cubes, co-fired (conversion efficiency =30%), were compared with electricity generation by coal, oil or natural gas. The results are summarized in Table 3.3.

Table 3.3. Amount of fossil fuel displaced by 100t of Miscanthus

Amount of fossil fuel displaced by 100t of Miscanthus	Savings in CO_2e	Savings as %
55.9 t of coal	148	94
31.0 t of natural gas	88	90
39.9 t of Fuel Oil	128	93

Table 3.4 provides an example of the calculations of net C gain for switchgrass vs. corn in producing ethanol to offset the CO_2 emissions of the gasoline that it replaces. The combination of lower energy requirements to both produce and convert switchgrass to ethanol, result in about 20 times higher CO_2 emissions savings per unit of land area with switchgrass compared to corn as seen in Table 3.4. Similar CO_2 offsets in producing and converting other bioenergy crops to biofuel types can be calculated.

Table 3.4. Comparative carbon flow in producing ethanol from switchgrass and **corn (McLaughlin and Walsh, 1998)**.

	Corn (kgC/ac)	Switchgrass (kgC/ac)
A. Production costs[a]	1492	598
B. Fuel replacement[b]	1578	2480
C. Net combustion savings[c]	86	1882
D. Soil carbon storage[d]	-----	1100
E. Total carbon reduction[e]	86	2982

[a]Includes agricultural production, chemical processing and distribution energy costs
[b]Replacement of gasoline at 19.94 kgC/GJ with ethanol. Coproduct credits were allowed for both corn (247kgC/ha) and switchgrass (437kgC/ha) based on energy equivalence of those coproducts.
[c]B-A.
[d]Assumes 1100kgC/ha/yr gain in soil organic carbon on land depleted by row cropping
[e]C+D.

3.1.5. Soil erosion

Soil erosion is the loss of top soil through wind or water. We focus on water erosion, because this is the most common type of erosion in Canada. Soil erosion leads to the degradation of soil quality, fertility and productivity (Christian and Riche, 1998). The risk of water erosion is high when there is no or limited soil cover, which is the case after ploughing and harrowing during the establishment of energy crops. However, the fast growth of perennial energy crops after establishment, their prolific rooting system, and increased level of rainfall canopy interception greatly minimize soil erosion in the second year and onwards. In annual bioenergy crops such as biomass sorghum, the cycle of soil cultivation and establishment is repeated yearly and consequently soil erosion rates could be higher compared to perennial crops; under such a situation, crop residue should be left on the field to reduce erosion intensity.

3.1.6. Phytoremediation

The use of energy crops and especially SRC plantations in phytoremediation of contaminated soil and water is a rapidly developing field and represents an important environmental co-benefit (Jankauskas and Jankauskiene, 2003). For example, the use of SRC (e.g. willow, poplar) to remove nitrates and other nutrients from municipal waste water (referred to as *'polishing'*) has been shown to have great potential (Aronsson et al., 2000; Aronsson and Bergstrom, 2001; and Mirck et al., 2005). Waste water polishing represents a potential win–win situation: it offers a cheap alternative to traditional sewage treatments, and provides an ideal fertiliser and water supply for the energy crops, resulting in improved yields (Aronsson and Bergstrom, 2001; Mirck et al., 2005; Perttu and Kowalik, 1997; and Perttu, 1999). These technologies are emerging in Minnesota. In Minnesota, probably the most promising agroforestry applications are the use of poplars to phytoremediate recycled animal wastewater and manure near *confined animal feeding operations* (CAFO's) and recycled wellhead water that is contaminated with high levels of nitrates and pesticides.

Extensive research has also examined the feasibility of using SRC plantations for the treatment of contaminated soil, especially the removal of cadmium (Cd). For example, within the UK, studies on contaminated brown field sites found that mixed poplar and willow SRC together with *Alnus* species were effective in reducing Zn and Cd levels (French et al., 2006). In addition, poplar genotypes have also been found to aid the breakdown of a range of other pollutants including trichloroethylene (TCE), atrazine, dioxane, TNT and methyl-tertiary-butyl-ether (Kassel et al., 2002; Aitchison et al., 2000; Burken and Schnoor, 1997; and Thompson et al., 1998). To date, the use of other energy crops such as Miscanthus and switchgrass for these applications has not been investigated and may be unwarranted because the biomass material would end up having higher concentrations of undesirable elements not suitable for the thermochemical conversion platform.

3.1.7. Biodiversity

Most energy crops, including switchgrass, Miscanthus and RCG offer several conservation benefits compared to conventional annual row crops and, as such, become 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. Several studies also show that the biodiversity of flora and fauna in Miscanthus and switchgrass fields is generally higher compared to conventional annual crops (Caslin et al. 2010; Semere and Slater, 2005). Positive impacts on the diversity of spiders, beetles and earthworms have also been observed in the case of the replacement rye with Miscanthus (Tolbert et al., 2002).

In general, the higher species-diversity in perennial grasses compared to annual crops is the result of the higher number of ecological niches (Coates and Say, 1999) and also the lower level of soil disturbance, the lower use of pesticides and herbicides. The lesser use of pesticides in the production of energy crops also reduces impact on other species in the ecosystem. By virtue of their perennial nature, perennial energy crops reduce the frequency of, and potential degradation associated with, tillage.

Chapter 4. Issues associated with accessing biomass plant source materials

The development of a viable bioenergy industry in Canada will require dependable delivery of logistically available biomass feedstock to conversion facilities. This implies that the production of bioenergy crops would require appropriate selection of the crops to ensure year-round availability tailored to local climatic biotic and edaphic stresses. A key to the appropriate selection of bioenergy crops lies with the planting materials to use. This chapter reviews sourcing and use of bioenergy crop planting materials and the related legal issues therein. Biomass crop planting or propagating materials could be seeds or vegetative parts. The principal aim of improving planting materials is to boost biomass yields, to improve resistance to both biotic and abiotic stresses (e.g. disease and pest resistance and drought or waterlogged resistance, respectively) and to enhance the quality of feedstock for use in producing power and electricity. Until recently, plant improvement depends solely on the use of traditional breeding techniques; farmers could save seeds for use in subsequent planting seasons. However, the introduction of modern innovations in breeding and agricultural biotechnology holds the promise of providing new feedstock with particular traits to overcoming the stresses and enhancing product quality. Such approaches involve long-term research and development with major investment in people and facilities with no guarantee of success. The compensation for such an investment and effort for the plant breeder or Biotechnology Company is *intellectual property (IP)* on each successful new variety or cultivar through an internationally agreed system of plant breeder's right.

Licensing agreements and other transfers of Intellectual Property

Intellectual property rights in agriculture (e.g. patents and plant variety protection certificates) are frequently used to protect technological advances. A *patent* is an exclusive right granted by an authorized agency (usually the federal governments in the US and Canada) that entitles the breeder/breeding company to prevent anyone else from making, using or selling the patented seed/planting material without authorization. These rights allow their owners to exclude competitors from making, using, offering for sale, or selling an invention for a limited period of time. As the pace of scientific discovery in agricultural biotechnology has accelerated over the past few decades, the use of patents and other intellectual property rights to protect these discoveries has increased tremendously. However, as with most other forms of property, the IP on planting materials may be bought, sold, or transferred through the process of granting licenses. The person to whom a license is granted is refereed to as the *licensee,* and the entity that provides the license is referred to as the *licensor* (Bagley and Dauchy, 1997*)*. Licensing agreements are used to grant limited, specified rights to use an IP. For example, software developers will typically license, not sell, their software to the customer. The license agreement will often contain many restrictions on how and by whom the software may be used. In agribusiness, the licensee could be the individual farmer, a cooperative group or seed distributor. A *specification* in a licensing agreement clearly stipulates the precise description of what IP is covered by the license. The licensee does not obtain rights to anything not set forth in the description of what is to be licensed. The *scope* of the license is the most important provision in many license agreements. The *scope-of-license provision* describes what the license may do with the licensed IP and spells out any limitations on the rights granted in the licensed IP. For example, the scope-of-license provision may contain limitations on issues such as: is the licence limited to only certain geographic regions or particular markets? Does the licence include the right to modify or improve the licensed technology? How long does the license last? On what terms, if any, can the license be renewed? (Bagley and Dauchy, 1997). The same principle applies in licensing of breeder's patent. Licensing the use of breeder's IP, through seed or planting materials production, allows payments (e.g. up-front lump sums, installment payments*, royalties* or some combination of these*)* to be collected on the planting material sold. In general, there are several types of licensing contracts/strategies used by biotech seed companies. For example, Monsanto's licensing contracts may include paid-up licensing, royalty fee, technology fee, contracts, and end-use fee. *Paid-up licensing* requires the *licensee* to pay an up-front fee to Monsanto for the right to use a particular process. Monsanto benefits from this strategy by generating funds in the early stages of technological development, helping to fund continuing research. The disadvantage of this strategy is that Monsanto profits only once and gives up profits from future sales covered by the agreement. Monsanto broadly licenses germplasm and trait innovations directly so farmers can realize the benefits from these inventions through the brands they prefer to plant on their farm. Thus, new cultivars could be licensed directly to the farmer by the germplasm company. Using a *technology fee* strategy is a way of making it clear that the cost of the seeds includes a technology fee. However, a technology fee could be problematic in that many farmers usually buy new GM seeds every few years and not annually; hence, the licensor (e.g. Monsanto) would not be paid every time a farmer uses the seeds. The problem with the technology fee strategy could be particularly pronounced in international markets where, in many countries, it is a tradition and common practice to save and plant seeds in subsequent years. *Contracts* would entail more interaction with the individual farmers, whereby the licensor could license the use of the seed directly to the farmer. For example, Monsanto believed that such contracts are educational, since the product users (the farmers) would understand that GM seed, as a new technology, requires a significant investment of time, resources, and special stewardship practices. Monsanto also hopes that these contracts would keep farmers from re-using seed and rather, purchasing it each year, as the contracts stipulates. The downside of contracts is that, to insure that farmers are not re-using the seeds, Monsanto would have to inspect individual farms, a daunting proposition. If the farmers were re-using the seeds, Monsanto would prosecute. ***Royalties*** can be based on many different measures, including unit sales, percentage of gross revenues, or percentage of profits *(Bagley and Dauchy1997)*. In agribusiness, the ***royalty fee*** is included in the sale of seeds or planting materials on per unit basis (e.g. $200/ha, or $0.34/vegetative propagule) and additional fees are collected for new planting of farm-saved seeds or planting materials. The royalty fee in this alternative is a one-time fee for all new plantations. As an example, a company could pay the licensor (e.g. Monsanto) a royalty based on the per-unit sale of the *Bt* Cotton seed germplasm, meaning Monsanto would benefit in the future but not immediately. Alternatively, the royalty fee may be collected as a percentage of total revenue for every harvest; this is sometimes refereed to as *end-use fee*. The use of such a licensing strategy means that farmers would pay a royalty fee only after the crops have been harvested. The benefit of this strategy is that both the technology provider/licensor (e.g. Monsanto) and the farmer would share in the risk and benefits. The strategy's downside, however, is that there is no way to control or prohibit farmers from reusing seeds. As examples of managing energy crop patent, BiCAN (a breeding company) demands only a one-time royalty fee be charged to farm operators for genetically modified

Miscanthus strains BiCAN has the right to propagate in Canada, while SUNY-ESF, the willow breeder in the US, charges a royalty fee of 4% of total revenue at every harvest for the willow varieties it developed. By comparison, since most switchgrass varieties currently grown in North America are native species, there is no patent on them; farmers can save seeds from previous seasons and grow them in subsequent seasons without any penalty as is done by the Don Nott farms (personal communications, Don Nott). However, when new genetically modified varieties with new traits are developed in the future, these new varieties will become subject to licensing with its attendant royalties.

Although a well-crafted license agreement can provide many protections, it is no substitute for thoroughly investigating the technology being licensed and the other party to the transaction; this is referred to as *due diligence* in legal jargon. For energy crop development, a due-diligence statement on compliance of the farmers with energy crop IP regulations should be included in biomass supply contracts, and suppliers should also be required to produce the supporting documents on energy crop source on a regular basis. An example of supplier agreements, provided in the University of Western Ontario Biomass Report (2009), is that of supply of flowers and plants from nurseries for resale to the general public by Wal-Mart:

"*All Vendor Partners shall comply with the legal requirements and standards of their industry under the national laws of the countries in which the Vendor Partners are doing business.*"

"Vendor Partners shall warrant to Wal-Mart that no merchandise sold to Wal-Mart infringes the patents, trademarks or copyrights of others and shall provide to Wal-Mart all necessary licenses for selling merchandise sold to Wal-Mart which is under license from a third party to protect intellectual property rights in the United States or elsewhere."

By this agreement, Wal-Mart reserves the right of inspection to assure the compliance of suppliers with the standards, and performs regular inspections. In Canada, the Canada Grain Commission controls the licensing of new varieties of grains.

The unauthorized making, use, or sale of a patented item (e.g. a breeder's seed) or process constitutes *patent infringement*. This is true whether or not the infringer was aware of the patent at the time of the infringement. Infringement can also occur if someone knowingly induces another to infringe a patent or knowingly contributes to another's infringement. The damages that can be awarded are often substantial, and may include paying over all profits earned with the infringing product. With energy crops as with other crops, farmers are obligated to comply with the laws governing IP rights. Non-compliance of these laws could impact not only the biomass suppliers (farmers, middlemen/aggregator) but also the end user; in this case the end-user could be considered a recipient of stolen property and liable to prosecution and penalties (personal communication, Dean Tiessen 2011). In the University of Western Ontario Biomass Report (UWO Report 2009), it was recommended that as part of the due-diligence measure in managing the IP issue in the development of energy crops, a compliance statement from farm operators with energy crop IP regulations be included in biomass supply contracts, and that all stakeholders in the supply chain be actively involved in contract development. This begs the question as to how best newly developed crop varieties should be managed.

As new energy crop varieties are being developed for higher yields, greater drought, pest and disease resistance and better fuel quality, new patents and licensing issues will emerge. To avoid any infringement by growers, biomass buyer/end-user would have to develop a workable approach to keep abreast with such new varieties.

Profile of major suppliers of bioenergy crop breeding planting materials

Although most current seed companies are focused on food and/or fibre crops, some are involved in genetically improving the performance of bioenergy crops either through conventional breeding techniques and/or genetic engineering. This section profiles some of these companies and local farms that provide planting materials.

1. New Energy Farms Group (NEF) ***http://www.newenergyfarms.com***

New Energy Farms (NEF) is the primary developer of Miscanthus in North America. NEF also supplies products and services to agricultural and end-use customers in the biomass feedstock supply chain. NEF currently has two large scale operational facilities for supply of Miscanthus rhizomes one in Canada (Ontario) and the other in the US (Georgia). From these sites NEF have the capability to produce tens of thousands of acres of Miscanthus rhizomes, roots and plugs derived from rhizomes. In Canada, NEF is at Leamington, Ontario; in the US the NEF site is located in the 4,000-acre vegetable unit of Tifton Georgia. NEF supplies products and services across the complete supply chain from farm to end users. These sites allow NEF to provide the most cost effective and high quality source of high quality rhizomes for North America. NEF has internal research and development activity focused on the development of new energy crop varieties and efficient crop production systems. NEF have over 15 years experience in the supply of high quality propagation material, mainly Miscanthus planting materials, well adapted to specific areas in the US and Canada with proper documentation of their pedigree. NEF does not import any material from the EU because of its unsuitability and inadequate documentation. According to Dean Tiessen, the President of NEF, *"with the opening of these sites NEF are providing Miscanthus at the volume and price demanded by farmers, to make large scale crop establishment possible and economic. This is part of our ongoing commitment to reduce the establishment cost for our customers for Miscanthus and other energy crops"'.*

NEF operates an 'Affiliate program' that provides additional technical support for Miscanthus growers. ***Solmass Ltd*** is the development component of the New Energy Farms Group, focused on developing technology in Miscanthus breeding, crop production systems and feedstock end use. In partnership with ***WH Loxton Ltd***, NEF has developed and supplies dedicated machinery to plant Miscanthus; these are fully automatic planters that can establish Miscanthus rhizomes at up to 50 acres per day. ***Pro-feedstock Ltd*** is part of NEW, focused on commercial supply of biomass feedstock (e.g. cubes, pellets, etc). Projects and supply agreements are supported and supplied by these agricultural affiliates and partners. Currently, rhizome propagation material supplied by NEF can be purchased with no onward royalties, for unencumbered use.

2. Ceres Corporation http://www.ceres.net

Ceres, Inc is a privately owned American company, based in Thousand Oaks, California. **The company** develops non-food grasses for advanced biofuels and biopower. Ceres partners with the *Samuel Roberts Noble Foundation (http://www.noble.org/)* to increase the effectiveness of conventional breeding, using genetic markers technology. Ceres is currently testing new switchgrass breeds that yield about 20 t/ha, compared with 12 t/ha conventional switchgrass in the U.S. Using advanced plant breeding and biotechnology, Ceres has analyzed 12,000 switchgrass genes and characterized the genetic variation associated with each one in order to create a trait database. This has been done in order to perfect cloning strategies that turn on/off specific genes that regulate traits such as yield, chemical composition, and drought tolerance. Ceres believes that this gene manipulation will enable bioenergy crops such as switchgrass to perform even better on marginal lands. The company's first products, high-yielding switchgrass cultivars and high-biomass sorghum hybrids, are now available under the Blade Energy Crops brand. Other crops in the pipeline include sweet sorghum, *Miscanthus* and energy cane.

In November 2009, Ceres announced that it plans to expand an advanced trait development project to increase biomass yields of several energy grasses by as much as 40% in coming years, while simultaneously decreasing the use of inputs such as nitrogen fertilizers. The project, which was selected by the U.S. Department of Energy from among 3,700 renewable energy proposals, will be funded in part by a $5 million research grant from the Advanced Research Projects Agency – Energy. The three-year project was expected to begin in late 2009. Ceres researchers will test its advanced traits in a variety of energy grasses such as switchgrass, sorghum and Miscanthus. Productivity and inputs requirements, such as fertilizer, will be evaluated as well as expected improvements to carbon and nitrogen cycles.

Considering that Ceres has made large investments in money and time in developing its seeds, the use of the company's seeds is covered by an agreement, "the Ceres Seed Use Agreement" that binds the seed purchaser with stipulated terms. The Seed Use Agreement provides the Grower, with the opportunity to purchase and use Ceres' branded seed (Ceres Seed) under the terms and conditions in the Agreement. By this agreement, the grower is only authorized to purchase and/or use Ceres Seed if he/she agrees to abide by all applicable laws and the terms of this Agreement. An example of such an agreement is as follows:

"1. LIMITED LICENSE – USE LIMITATIONS.

Ceres, Inc. and its subsidiaries (Ceres) has a proprietary interest in Ceres Seed as a result of patents, plant variety protection rights or plant breeders' rights pending or granted and/or trade secret information or proprietary know-how contained in the genetic materials of the seed, unless designated otherwise on the seed label attached to the seed bags. Ceres offers Ceres Seed for sale subject to the terms of this Agreement. The purchase price for Ceres Seed represents a license fee for the limited use of the proprietary and intellectual property interests Ceres has in Ceres Seed. Please refer to the seed label for specific information regarding patents and/or plant variety protection or plant breeders' rights certificates.

Under this Limited License Agreement, GROWER MAY:

- Use Ceres Seed solely for producing a single commercial crop or a multi-year stand for perennials.

Under this Limited License Agreement, GROWER MAY NOT:

- Use Ceres Seed, or any parental line seed which may be found therein, or any resultant plants, seed, mutants, sports or plant tissue from any of the foregoing, for any breeding, tissue culture, sexual or asexual propagation, seed production, reverse engineering, genetic fingerprinting, molecular or genetic analysis or engineering, or research (except research on biomass (excluding any seed) grown from Ceres Seed not resulting in the reproduction of such biomass), other than the production of a single commercial crop or multi-year stand for perennials.
- Sell, transfer, export, sublicense, give or supply Ceres Seed to any other person or entity for any purpose.
- Save, clean, condition or sell progeny of Ceres Seed for the purpose of planting a subsequent crop.

All rights not specifically granted are reserved by Ceres.

2. LIMITATION OF WARRANTIES, LIABILITY AND REMEDIES.

IMPORTANT NOTICE: Successful farming requires a high degree of skill. The performance of seed and crops are greatly impacted by numerous factors and conditions beyond the control of Ceres and its authorized seed dealers ("Seed Dealers") including, among other things, environmental conditions, such as sunlight, moisture, temperature, and soil composition; adverse weather conditions, such as drought, excessive rainfall, high wind; pests, diseases, and individual farming practices. Grower assumes all risks that these factors and conditions will adversely impact the performance of the seed and crop produced from the seed. Ceres does not guarantee crop yield or performance.

EXCLUSIVE WARRANTY. Ceres' sole and exclusive warranty on the seed is that the seed conforms to the label description on the bag and/or bag tags within reasonable tolerances.

ALL OTHER WARRANTIES ARE EXPRESSLY DISCLAIMED. CERES AND ITS SEED DEALERS MAKE NO OTHER EXPRESS WARRANTY ON THIS SEED. CERES AND ITS SEED DEALERS ALSO DISCLAIM ALL IMPLIED WARRANTIES, INCLUDING ANY IMPLIED WARRANTY OF MERCHANTABILITY OR IMPLIED WARRANTY OF FITNESS FOR A PARTICULAR PURPOSE. CERES AND ITS SEED DEALERS UNDERTAKE NO RESPONSIBILITY FOR THE QUALITY OF THE SEED, AND ASSUME NO RESPONSIBILITY THAT THE GOODS WILL BE FIT FOR ANY PARTICULAR PURPOSE

FOR WHICH GROWER MAY BE BUYING THE SEED. TO THE EXTENT PERMITTED BY FEDERAL AND STATE LAW, THE SEED IS BEING SOLD ‘AS IS.’

LIMITATION OF LIABILITY AND REMEDIES. Grower's sole and exclusive remedy for any and all losses or damages resulting from the use of the seed, whether such claims are based in contract, negligence, strict liability, tort, or any other theory of recovery or remedy, shall be the return of any amounts paid for the seed. NEITHER CERES NOR ITS SEED DEALERS SHALL BE LIABLE FOR ANY INDIRECT, REMOTE, INCIDENTAL, CONSEQUENTIAL, SPECIAL OR PUNITIVE DAMAGES OR LOSS OF PROFIT.

PROMPT NOTICE OF CLAIMS REQUIRED. As a condition to any liability of Ceres and its Seed Dealers, any and all claims for losses or damages resulting from the use of this seed must be presented immediately to Ceres so that the claim may be investigated and the seed or crop inspected. All claims must be presented to Ceres within thirty (30) days after the condition or event giving rise to the claim is discovered, or should have been discovered, or prior to the harvest of the crop, whichever comes first, or such claims shall be deemed to be waived by Grower.

This Limitation of Warranties, Liability and Remedies MAY NOT BE MODIFIED OR AMENDED VERBALLY OR IN WRITING. If a court determines that any term or provision of this Limitation of Warranties, Liability, and Remedies is unenforceable, then such term or provision shall be stricken and the remainder of the Limitation of Warranties, Liability, and Remedies shall remain enforceable.

3. BINDING ARBITRATION FOR PERFORMANCE-RELATED CLAIMS BY GROWER.

It is expressly agreed that Grower and any person claiming any interest in Grower’s crop shall submit any claim or action made or asserted regarding the performance of such seed, whether involving Ceres, its Seed Dealers, or both, to binding arbitration. The parties acknowledge that this transaction involves interstate commerce. The parties agree that arbitration shall be conducted pursuant to the provisions of the Federal Arbitration Act, 9 U.S.C. § 1 et seq., and administered under the Commercial Dispute Resolution Procedures established by the American Arbitration Association. Such arbitration shall take place in the capital city of the state in which such crops were grown, or in any other place as the parties may decide by mutual agreement. In the event that a claim is not amicably resolved within 30 days of Ceres’ receipt of the Notice of Claim required by this Agreement any party may initiate arbitration.

4. FORUM SELECTION FOR ALL OTHER CLAIMS.

The parties consent to the sole and exclusive jurisdiction and venue of the California State Courts having jurisdiction in San Francisco County, California, or, in the event of federal jurisdiction, the United States District Court for the Northern District of California for all claims arising out of or in any way connected with this Agreement and/or the use of Ceres Seed, except for seed performance-related claims made by Grower.

5. CHOICE OF LAW.

This Agreement shall be construed and governed under the laws of the State of California.

6. GENERAL TERMS.

When this Agreement becomes effective, it will remain in effect until either Ceres or the Grower chooses to terminate this Agreement. New or additional terms to this Agreement, if any, will be mailed to Grower once a year. Continuing use of Ceres Seed after receiving any new or additional terms constitutes Grower's acceptance and agreement to be bound by the new terms.

If either party elects to terminate this Agreement, it must deliver written notice of the termination to the other party. The Grower's written notice must be mailed to: Ceres, Inc., 1535 Rancho Conejo Blvd., Thousand Oaks, CA 91320. If this Agreement is terminated by the delivery of a written notice, the Grower's responsibilities and obligations shall survive and continue in effect as to all Ceres Seed purchased or received before termination and crops grown from such Ceres Seed.

The Ceres name, all Ceres logos, and all Ceres trademarks (for example, "Blade Energy Crops") may only be used by Grower in a manner that is previously approved in writing by Ceres.

This Agreement governs the relationship between Ceres and Grower and supersedes all other agreements. A Seed Use Agreement is also printed on the seed bags of Ceres Seed (Bag Agreement). Where there is a conflict between the terms of this Agreement and the Bag Agreement, the terms of this Agreement shall prevail.

If any term or provision in this Agreement is determined by a court of competent jurisdiction to be void or unenforceable, then such term or provision shall be stricken and the remainder of the Agreement shall remain in effect and enforceable.

Grower shall pay the purchase price, all fees, and charges that are due or that are invoiced for Ceres Seed.

Grower shall permit Ceres to examine and copy any records and receipts that may be necessary to determine whether Grower has misappropriated or infringed Ceres' proprietary interests that are licensed herein.

If Grower breaches this Agreement, then Grower's limited-use license shall terminate immediately. Should Grower's limited-use license terminate due to Grower's breach, the Grower's responsibilities and obligations that arose before termination shall survive and continue in effect. If Ceres prevails in litigation or arbitration to enforce this Agreement, Grower agrees to pay Ceres' attorney's fees and costs and other expenses incurred in the enforcement of this Agreement".

3. Mendel Biotechnology http://www.mendelbio.com

Mendel Biotechnology Inc. is a closely-held private company founded in 1997. Headquartered in Hayward, California, the company has been a pioneer in the application of *functional genomics* to the study of plant genes. Mendel has identified and patented the use of genes that control many aspects of plant growth and development, and is using such inventions to develop or co-develop new plant varieties with improved productivity and quality. Mendel Biotechnology is co-owned by Monsanto. *Mendel's BioEnergy Seeds (MBS)* division is developing new varieties of very productive bioenergy grasses to enable the delivery of large scale supplies of high value biomass feedstocks produced on marginal and under-utilized lands. Mendel's product portfolio includes research and development program focused on Miscanthus; the company applies its validated trait technology and advanced breeding techniques to develop superior, proprietary Miscanthus varieties and other energy crop products. British Petroleum (BP) is a shareholder of Mendel in developing Miscanthus varieties. In 2007, Mendel acquired the entire Miscanthus breeding program from *Tinplant Biotechnik und Pflanzenvermehrung GmbH*, a German breeding and plant science company. The Tinplant team has spent about 15 years in research and breeding of more than 1,000 different Miscanthus varieties to improve the plant's properties. Before its acquisition, Tinplant and New Energy Farms (NEF) had formed a joint venture, *Cantus Bio Power* (www.cantusbiopower.com), which owns propriety genetics of Miscanthus, claimed to be suitable for Ontario. Mendel also has relationships with other leading agricultural, forestry and horticultural companies for the commercialization of improved seed and plant products. Additional species in development include ***high-biomass sorghum*** through Mendel's collaboration with *MMR Genetics and Richardson Seeds* (http://www.richardsonseeds.com/).

4. The Monsanto Company http://www.monsanto.com

The Monsanto Company is a US-based multinational agricultural biotechnology corporation founded in 1901 and headquartered in Missouri. Monsanto is a leading producer of genetically engineered/modified (GE/GM) seeds, and currently provides the technology in 90% of the genetically engineered seeds used in the US market. Monsanto has a biofuel department that currently focuses on conventional breeding for corn varieties. Monsanto is also a major a player in the development of Miscanthus through Mendel Biotechnology. Monsanto is interested in the fuel potential of switchgrass, and currently collaborates with Ceres Corporation to research its possibilities.

Monsanto scientists became the first to genetically modify a plant cell in 1982. Five years later, Monsanto conducted the first field tests of genetically engineered crops. Much of Monsanto's seed products are specifically genetically modified, to make them resistant to Monsanto produced agricultural chemicals, such as "Round Up" herbicide. Monsanto and its subsidiaries (including *Asgrow*® and *DeKalb*®) currently own more than 400 separate plant technology patents. Agricultural companies such as Monsanto are able to patent seed trait technology because it is considered intellectual property protected in the U.S. Critics of the seed technology patents contend that seed patents financially hurt farmers because farmers must purchase new seed every year and cannot save the seed from the previous growing season. Other critics say Monsanto is being unethical by patenting its technology, as you should not be able to patent a natural product; Monsanto disagrees. In the words of their officials “With the application of this science, we are now able to reduce pesticide use, we’re going to be able to reduce the necessity for irrigation or rain for our drought-tolerant products, and we’re going to be able to reduce the need for certain fertilizers like nitrogen by enabling these plants to do more with less in the future.”

In June 2007, Monsanto acquired ***Delta & Pine Land Company***, a company that had patented a seed technology nicknamed *Terminators*. This technology, which was never known to have been used commercially, produces plants that have sterile seeds so they do not flower or grow fruit after the initial planting. This prevents the spread of those seeds into the wild, however it also requires customers to repurchase seed for every planting in which they use *Terminator* seed varieties. In recent years, widespread opposition from environmental organizations and farmer associations has grown, mainly out of the concerns that hypothetical seeds using this technology could increase farmers' dependency on seed suppliers.

Monsanto is notable for its involvement in high profile lawsuits, as both plaintiff and defendant, over issues related to its products. Monsanto has also made frequent use of the courts to defend its patents, particularly in the area of biotechnology. The usual claim involves violation of a technology agreement that prohibits farmers from saving seed from one season's crop to plant the next, a common farming practice. For example, throughout 2004 and 2005, Monsanto filed lawsuits against many farmers in Canada and the U.S. on the grounds of patent infringement specifically the farmers' sale of seed containing Monsanto's patented genes. In some cases, farmers claimed the seed was unknowingly sown by wind carrying the seeds from neighboring crops, a claim rejected in the courts (see *Monsanto Canada Inc. v. Schmeiser*). By a 5-4 vote in late May 2004, that court ruled that "by cultivating a plant containing the patented gene and composed of the patented cells without license, the appellants (Canola farmer ***Percy Schmeise***) deprived the respondents (Monsanto) of the full enjoyment of the patent." With this ruling, the Canadian courts followed the U.S. Supreme Court in its decision on patent issues involving plants and genes. In 2004, Switzerland's Syngenta launched a US lawsuit charging Monsanto with using coercive tactics to monopolize markets. There are several lawsuits going both ways between Monsanto and Syngenta. In 2006, the Public Patent Foundation filed requests with the United States Patent and Trademark Office to revoke four patents that Monsanto has used in patent lawsuits against farmers. In the first round of reexamination, claims in all four patents were rejected by the Patent Office in four separate rulings dating from February through July 2007. On March 30th, 2011 a group consisting of over 60 family farmers, seed businesses and organic agricultural organizations in Canada and the US, filed a lawsuit against Monsanto Company to challenge the chemical giant's patents on genetically modified seed. The plaintiffs say they are being forced to sue pre-emptively to protect themselves from being accused of patent infringement should they ever become contaminated by Monsanto's genetically modified seed.

5. Performance Plants Inc. (PPI) http://www.performanceplants.com

The Performance Plants Inc. is a Canadian-based agribusiness company established in 1995. PPI is a global leader in agricultural and biofuel biotechnology. The Company's Head Office and Trait

Development centre are located in Kingston, Ontario, and has research facilities in Kingston, Saskatoon, and Waterloo. The company has technologies that achieve higher and more consistent crop yields through improved heat tolerance, drought tolerance and reduced water requirements. To date PPI has patented and licensed its breakthrough yield protection technology to some of the world's leading seed companies such as *Syngenta* (*www.syngenta.ca/*), *Stine* (*www.stineseed.com/*), *RiceTec* (*www.RiceTec.com/*), and *The Scotts Miracle Gro* (*www.thescottsmiraclegrocompany.com/*). In addition, the Company is improving the cost and quality of bioenergy feedstocks. Currently, PPI is actively involved in growing bioenergy crops to replace coal at Lafarge Canada Inc.'s cement plant in Bath, Ontario. New varieties of energy crops, especially Miscanthus, are being developed by PPI.

6. Nott Farms

The Nott Farms is a private farm owned by farmer Don Nott and his family and located in Clinton, Ontario. Don Nott is Ontario's leading developer and producer of the switchgrass bioenergy crop. Nott farms established about 140 ha of switchgrass in the spring of 2006, considered the largest commercial switchgrass plantation in Canada to date. Mr. Don Nott initially obtained his seeds for planting (Cave-in-Rock) from *Ernst Seed Company* of Pennsylvania, USA; seeds were saved from this initial establishment for planting in subsequent years without any encumbrance. Since current switchgrass seeds being used have no proprietary, the Nott farm can become a potential switchgrass seed supplier to prospective switchgrass farmers in the future.

7. Ernst Seed Company

Ernst Seed Company is an American seed company based in Meadville, PA. The company specializes in native and naturalized seeds and plant material of Eastern North American ecotypes, cleaned and tested to U.S. standards. Ernst supplies the highest quality seeds, mixes, and bioengineering products for restoration, reclamation, and conservation applications. Currently, Ernst Seeds is on of the largest and most experienced switchgrass seed producers in the world; the company has more than 20 years experience in establishing, managing, and harvesting switchgrass seed and biomass. The company also has expanded processing, treating, and storage facilities. As biomass production from switchgrass can vary greatly from one region to another, the company assists in selecting switchgrass varieties that are well suited to the growing conditions of the customer's area, using the company's *Switchgrass Variety Zone Map*. As part of its mixed energy crop scheme, Ernst Seed Company also provides advice on mixing switchgrass with other native grasses and legumes to create a biomass mix that can be more productive than a monoculture of one species. Examples of the native grasses include *big bluestem, Indianagrass, coastal panic grass, cordgrass*; the legumes include showy *tick trefoil, wild senna, and partridge pea.* Ernst Conservation Seeds is also actively involved in numerous cooperative efforts with government agencies, universities, and groups in the private sector who are interested in increasing the use of switchgrass biomass in many applications. Seeds **p**urchased from Ernst Seed Company have no proprietary and therefore farmers are able to save seeds and use them in subsequent years.

CHAPTER 5: Estimates of energy crop biomass supply in Ontario

This chapter attempts to estimate the potential total supply of biomass from the five selected energy crops based on available land for producing crops (i.e. tillable land) and the productivity (yields per unit area) under Ontario conditions. It must be noted that estimating Ontario biomass supply is quite different from projecting the size of the Ontario biomass market for two major reasons: (1) this study is limited to biomass supply of only five selected energy crops and excludes all other agricultural biomass sources, including all other potential energy crops, and (2) a *market size* is a product of the number of buyers (X), the quantity of product purchased by an average buyer in the market per year (Y) and the price of an average biomass unit (Q) [i.e. market size=X*Y*Q]; we do not have information on any of these parameters since a biomass market does not yet exist in Ontario. In estimating Ontario biomass supply, we made several assumptions and created multiple scenarios, with each scenario providing different biomass supply estimates. The estimates are based on tillable land area and productivity of the five regions of Ontario, namely Southern, Western, Eastern, Central and Northern regions as depicted in the map, Figure 5.1.

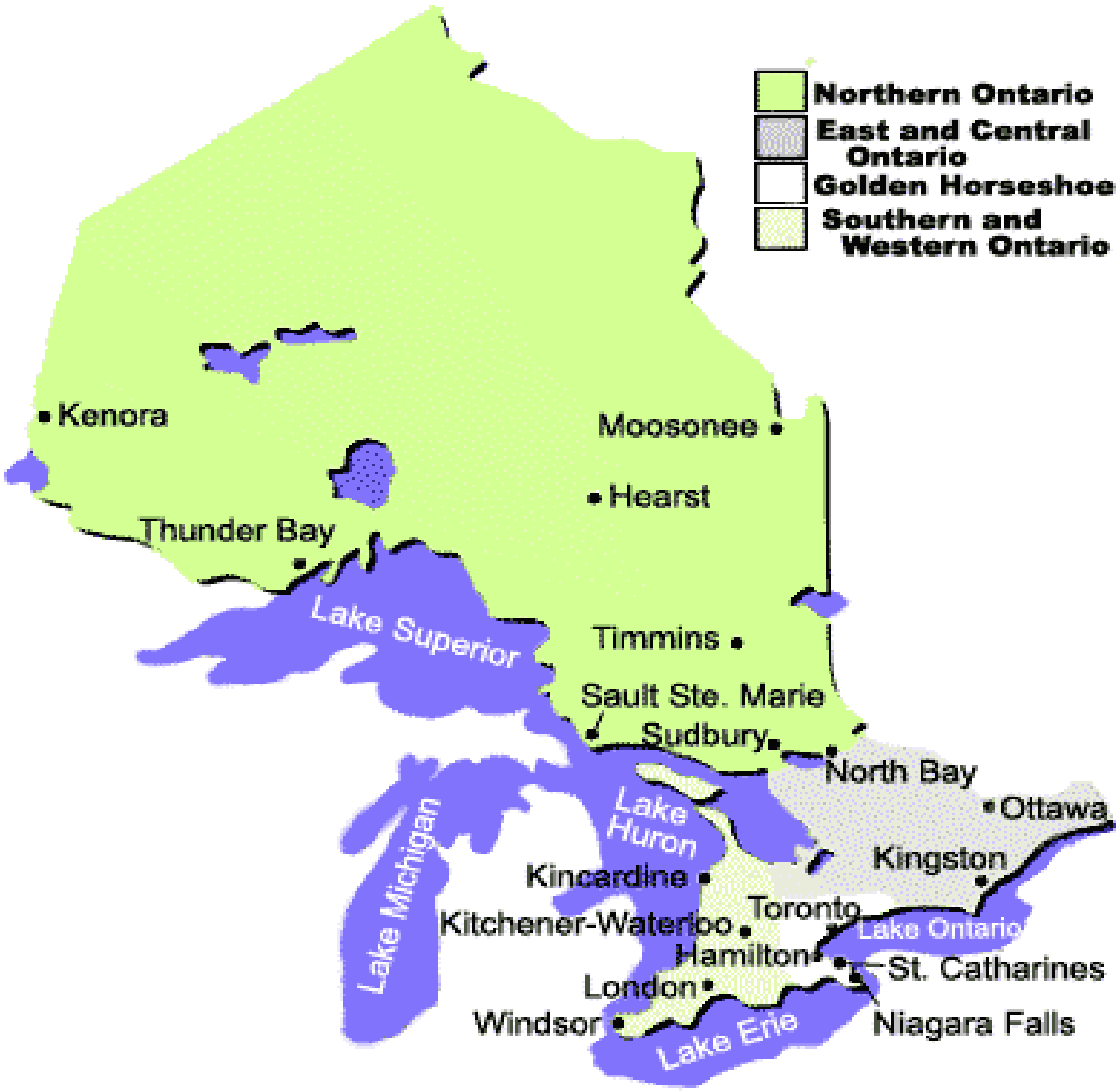


Figure 5.1. The five geographic regions of Ontario, showing the major cities and lakes

5.1. Potential Land Base for Producing Energy Crops

We first examined the land base of Ontario to determine the capability of lands for growing biomass/energy crops. 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 5.1 provides definitions and descriptions of these land classes.

Table 5.1: 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 general, the best lands (Class 1 lands) are mainly used to grow vegetables and fruits, and Classes 1 to 4 lands are considered capable of sustained production of common field crops, such as corn, soybean, and wheat (Table 5.1).

The need for management practices increases, and/or the possible range of crops decreases, from Class 1 to Class 4. 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 potential land base for producing crops is limited to Classes 1 to 5 lands. We consider Classes 1-3 to be ***"high-valued lands"*** for growing most field crops including vegetables and fruit trees and Class 4 and 5 lands as ***"marginal lands".***

Potential biomass productivity in each Ontario region 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 is, 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 area on regional basis, all geo-township data in all counties for each particular region was pooled (Table 5.2). The data from Table 5.2 indicate that Southern and Western regions have the largest tillable land whilst Northern Ontario has the least. Also, tillable land area in Eastern Ontario is larger than that in Central Ontario.

Table 5.2. Tillable land area (ha) by Ontario Region.

	LAND CAPABILITY CLASSES (ha)					
Ontario Regions	**1**	**2**	**3**	**4**	**5**	**Total**
Southern Ontario	238,102	876,664	414,109	37,138	39,332	1,605,345
Western Ontario	724,831	254,067	239,130	73,112	130,091	1,421,231
Central Ontario	165,830	113,526	122,839	118,976	84,424	605,595
Eastern Ontario	32,005	312,567	304,841	148,471	65,166	863,050
Northern Ontario	10,775	6,903	18,002	19,735	11,262	66,677
Total Ontario	**1,171,543**	**1,563,727**	**1,098,921**	**397,432**	**330,275**	**4,561,898**

It must be noted that data from some counties within a region have not been used in this study either because no data are unavailable or are found to be unreliable. For example, data from Ottawa county in the Eastern region, Muskoka county, Parry Sound county and Haliburton county in Central Ontario are excluded from this analysis because either there were no data available, or the data provided are found to be unreliable. In the case of the Northern region, available and reliable data were found for only Manitoulin and Nipissing Counties. The exclusion of data from these counties explains the disparity in our total land area of 4.56 ha (Table 5.2) and total farm land area of 5.39 ha reported in the Ontario 2006 census data. Figures 5.2-5.5 are maps showing the distribution of land classes according to CLI in Ontario.

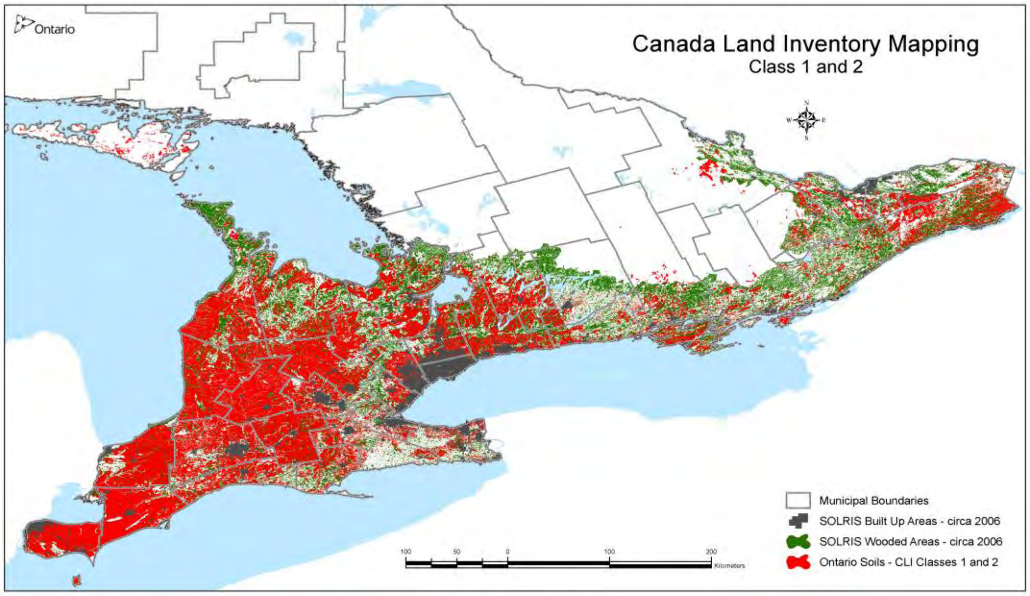


Figure 5.2: Map of Class 1 and 2 Soils in Ontario (OMAFRA, 2009)

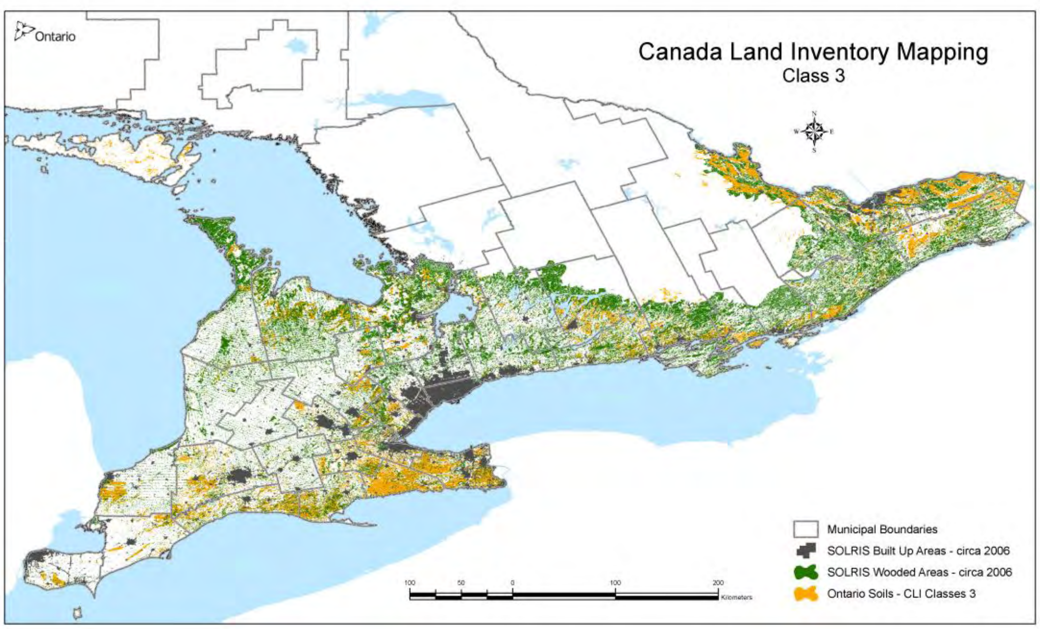


Figure 5.3: Map of Class 3 Soils in Ontario (OMAFRA, 2009)

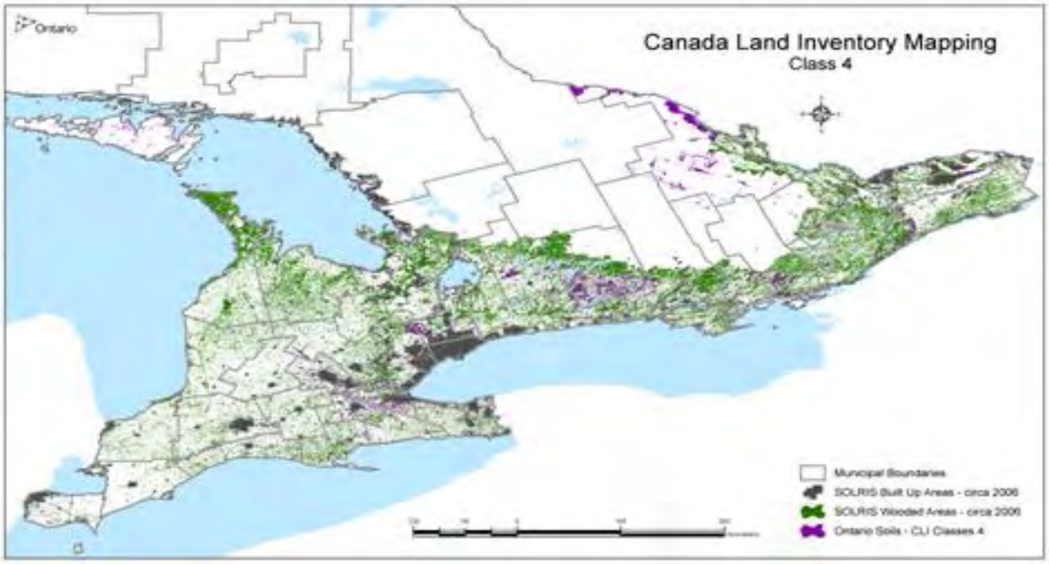


Figure 5.4: Map of Class 4 Soils in Ontario (OMAFRA, 2009)

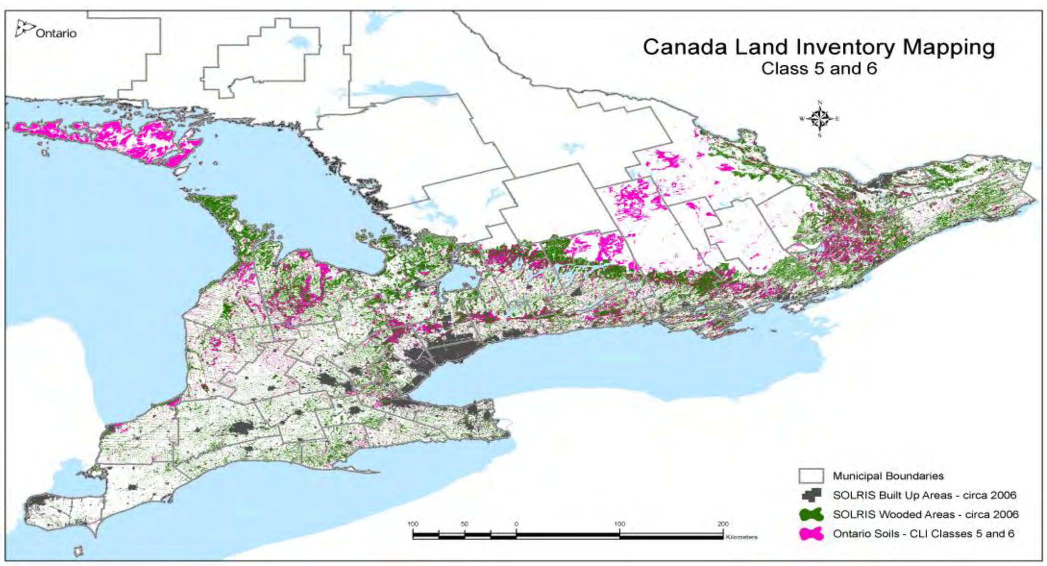


Figure 5.5: Map of Class 5 and 6 Soils in Ontario (OMAFRA, 2009)

As an example, the available tillable land area for the Municipality of Chatham-Kent is summarized in Table 5.3.

Table 5.3. 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).

In estimating biomass supply from the five selected energy crops, we made the following assumptions:

1. There is no restriction on the conversion of any land class to energy crop production, and the proportions of land classes that would be allocated to production would be dictated by economic considerations.

2. Biomass productivity (yield/land area) on *"high-valued lands"* is assumed to be higher than that on "*marginal lands"*. Although a recent US study by Wullscheleger et al. (2010) found no significant statistical correlation between productivity and land capability class, for either lowland or upland ecotypes of switchgrass, it is likely that there is still some degree of yield response in more spatially explicit situations.

3. To estimate potential biomass production, scenarios involving the conversion of 5%, 10%, 25%, 60% and 100% of tillable lands in a region are considered. Results of these scenarios are discussed under the individual biomass crops

4. Biomass is spring harvested and productivity is expressed on dry matter basis (tDM/ha)
5. Biomass recovery from the field is 100%.

Potential biomass yields of the selected energy crops under Ontario conditions

Miscanthus

Compared to switchgrass, Miscanthus production in Ontario is more recent. Thus, there is even less distribution of field trials on this crop compared to switchgrass. Most of the reported post-establishment Miscanthus 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. Indeed, so far, data collection from Ontario studies on Miscanthus yields are only 3 years old. 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, we do not assume any one specific type of Miscanthus in this analysis, but assume the mean yield of 12.0 tDM/ha for the Classes 1 and 2 lands (preliminary spring harvested mean yield for Nagara=13 tDM/ha, and for Amori=11 at Elora on Classes 1 and 2 lands); 11.0 tDM/ha on Class 3 land (i.e., 90% of the productivity of very high valued lands), 8.0 tDM/ha on Class 4 land (i.e., 70% of the productivity of very high valued lands), and 7.0 tDM/ha on Class 5 land (i.e., 60% 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.

Switchgrass

Unlike Miscanthus, switchgrass has been studied extensively in Canada. There is however limited information on field trials and productivity of biomass crops in Ontario. 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). However, when harvesting is done in the spring (overwintering), about 20-30% reduction in harvestable yields is occurs, although the resulting material may have improved combustion quality (Adler et al., 2006; Colley et al., 2006; Shaw and Tabil 2007). Spring harvested yields in Elora at the University of Guelph Research Station indicates that Cave-in-Rock and Shelter cultivars have 6.8 tDM/ha and 4.4 tDM/ha respectively. Don Nott reported yields of about 6-7tDM/ha on lands capable of producing corn, soybean and wheat. For the sake of this study, we assume that the mean potential yield of switchgrass is as follows: 7 tDM/ha on Classes 1-2 lands; 6.3 tDM/ha on Class 3 land; and 5.6 tDM/ha on Classes 4 and 5 lands (switchgrass adapts well on marginal lands).

Reed Canarygrass (RCG)

Very little work has been done on RCG in Ontario. However, it has been reported that there are only slight differences in yields among RCG cultivars, and the highest yields are obtained when harvested at heading (Hall, 2008). The average yield of *Palaton* in Southern Ontario trials is 9.5 tDM/ha; in Northern Ontario trials, it is 8.0 tDM/ha (Chisholm 1994). We assume 8 tDM/ha for Classes 1-2 lands; 7tDM/ha for Class 3 land, and 6 tDM/ha for Classes 4 and 5 lands.

High-biomass Sorghum (HBS)

Like RCG, very little work has been done on HBS in Ontario. However, much work on this plant can be found in several locations across the US (Miller et al., 1989; Hallam et al., 2001; Rooney et al., 2007; CERES, 2010). For example, in Iowa, Hallam et al. (2001) compared perennial grasses with annual row crops and found that sorghum had the highest yield potential, averaging over 35 tDM/ha and also performed well when intercropped with legume species. Miller et al (1989) identified specific experimental hybrids that optimized yield potential under multicut and single cut production schemes; mean cumulative dry-matter yields were 22 t/ha, 23 t/ha and 22 t/ha for harvest sequences of two cuts at 90 days, two cuts at 120 days and 60 days and a single cut (180 days), respectively. In Canada, Agricultural Environmental Renewal Canada (AERC) with research facilities in Delhi, Ontario, has developed varieties and hybrids that can be grown under climatic conditions across Canada. From 2002 to 2005, AERC research focused on developing high-biomass sorghum (HBS); results from this research showed dry matter yields ranging from 9 to 11 tDM/ha, about the same as corn silage. More recent research from 2006 to 2008 showed hybrids could yield 45.3 to 55.3 t/ha of green biomass. In this study, we assume 11 tDM/ha of high-biomass sorghum for Classes 1-2 lands; 10 tDM/ha for Classes 3 land and 9 tDM/ha for Classes 4 and 5 lands.

Hybrid Poplar

Growth and yield of poplars depend on geographic location, site quality, clone, age, spacing, and plant management (silvicultural) conditions such as frequency of harvesting. Yield ranges are therefore wide and varied. In this study we assume the following annual yield estimates: 16 tDM/ha for Classes 1 and 2 lands; 9 tDM/ha for Classes 3 and 4 lands; and 7 tDM/ha for Class 5 lands.

A summary of the mean energy crops yield estimates for land capability classes is presented in Table 5.3.

Table 5.3. Mean energy crops yield estimates for land capability classes (tDM/ha)

Land Classes	**1**	**2**	**3**	**4**	**5**
Crops	***High Valued lands***			***Marginal lands***	
Miscanthus	12	12	11	8	7
Switchgrass	7	7	6.3	5.6	5.6
Reed canarygrass	9.5	9.5	8	7	6
High biomass Sorghum	11	11	10	8	7
Hybrid Poplar	16	16	9	9	7

Potential Biomass Production from the Selected Energy crops in Ontario

Scenario 1: For each energy crop source, 5%, 10%, 25%, 60% and 100% land use with their corresponding biomass yields determines biomass production/supply.

Table 5.4. Potential Biomass Production from Energy crops in Ontario (tDM/yr)

	5%	**10%**	**25%**	**60%**	**100%**
Miscanthus	2,520,144	5,040,289	12,600,743	30,241,651	51,730,896
Switchgrass	1,507,268	3,014,534	7536348	18,087,152	31,074,954
Reed canarygrass	1,977,012	3,954,022	9,885,072	23,724,065	40,702,233
High-biomass sorghum	2,328,435	4,656,869	11,642,192	27,941,137	47,896,705
Hybrid Poplar	2,977,177	5,954,361	14,885,920	35,726,055	61,037,584

Table 5.4 summarizes the total annual potential biomass production from the five energy crops in Ontario, assuming 100% harvesting recovery. For example, at 5% land use for all the five land classes with their corresponding biomass yields, about 2.5 million tDM of Miscanthus can be potentially produced across Ontario; at 60% land use, over 30 million tDM of Miscanthus can be supplied. The corresponding values for High-biomass Sorghum (HBS) are about 2.3 million and 27 million tDM, respectively. If all tillable land area in Ontario is used for producing switchgrass, just over 31 million tDM can be potentially supplied annually. It must however be noted that in practice, not all land in a region (or even a County) should be used for growing the same energy crop type since this would increase disease and pest build-up.

Experiences in Europe suggest that biomass production from energy crops could fluctuate between 10% and 15% due to normal changes in weather conditions (DTI, 2003). For example, biomass yield reduction by 12% would reduce total Ontario yields of Miscanthus to about 2.2 million tDM if 5% tillable land area is used for the production; this yield would be further reduced to 1.1million tDM assuming only 50% harvest efficiency. In effect, constraints such as harvesting efficiency, adverse weather conditions and possible disease and pest infestation could drastically reduce potential biomass supply far below the levels provided in Table 5.4. For example, Pyter et al (2007) reported that a 2006 drought in Illinois reduced Miscanthus yield by 31%. Details of biomass production in each region, using percentage tillable land area and land classes with their corresponding yields can be found in ***Appendices B1 and B2***.

Using mixed-crop scheme scenarios.

Since large acreages of monoculture should be avoided in producing energy crops, mixed-crop schemes could be adopted. Possible mix-schemes of bioenergy crops are presented as Scenarios 2 to 6. Scenario 2 is constituted by using 25% of all tillable land (i.e. Classes 1-5 lands) for producing Miscanthus, switchgrass, Poplar and High-biomass sorghum in all Ontario regions Except the Northern region (Table 5.4). This mix could provide over 46 million tDM of biomass per year. In scenario 3, we assume that only 10% of tillable land is used for Miscanthus production, and 25% and 60% of all tillable land is used for producing SG and HBS respectively (Table 5.5). Under such a mix, total biomass production would be almost 45million tDM/yr, assuming 100% recovery during harvest.

Table 5.4. Mixed-crop scheme Scenario 2

Ontario Regions	25% Misc.	25% SG	25% Poplar	25% HBS	Total
Southern	4,626,212	2,710,125	5,543,211	4,243,993	17,123,541
Western	3,968,198	2,374,194	4,845,810	3,663,690	14,851,892
Central	1,561,584	967,113	1,809,268	1,461,034	5,798,999
Eastern	2,283,014	1,382,220	2,512,284	2,120,661	8,298,179
Northern	-	-	-	-	-
Ontario Total	12,439,008	7,433,652	14,710,573	11,489,378	**46,072,611**

Table 5.5. Mixed-crop scheme Scenario 3

Ontario Regions	10% Misc.	25% SG	60% HBS	Total
Southern	1,850,476	4,626,212	10,185,556	16,662,244
Western	1,587,274	3,968,198	8,792,830	14,348,302
Central	624,634	1,561,584	3,506,450	5,692,668
Eastern	913,215	2,283,014	5,089,587	8,285,816
Northern	-	-	-	-
Ontario Total	4,975,599	12,439,008	27,574,423	**44,989,030**

Scenario 4 consists of using 90% of all tillable for producing Miscanthus with 5% each for SG and Poplar in the mix; no biomass is produced in the Northern region (Table 5.6). This scenario would provide 50million tDM/yr.

Table 5.6. Mixed-crop scheme Scenario 4

Ontario Regions	90% Misc.	5% SG	5% Poplar	Total
Southern	16,654,337	542,022	1,108,635	18,304,994
Western	15,480,795	474,846	969,172	16,924,813
Central	5,621,649	193,422	361,854	6,176,926
Eastern	8,218,841	276,440	502,448	8,997,729
Northern	-	-	-	-
Ontario Total	45,975,622	1,486,730	2,942,109	**50,404,461**

In a crop mix scenario where we have 90% tillable land use for producing RCG in Northern Ontario with 5% and 25% land use for producing Misc and SG respectively in the other regions, a total of about 9.4 million tDM/yr of biomass could be supplied (Table 5); this is scenario 5.

Table 5.6. Mixed-crop scheme Scenario 5

Ontario Regions	**5% Misc.**	**25% SG**	**90% RCG in North**	**Total**
Southern	542,022	2,710,125	-	3,252,147
Western	474,846	2,374,194	-	2,849,040
Central	193,422	967,113	-	1,160,535
Eastern	276,440	1,382,220	-	1,658,660
Northern	-	-	465,906	465,906
Ontario Total	1,486,730	7,433,652	465,906	**9,386,288**

Scenario 6 assumes 10% land use for producing Miscanthus and switchgrass, 60% land use for High-biomass sorghum and 20% for Poplar with no RCG in the mix; the entire northern region is biomass production (Table 5.7). A total of 47million tDM can be supplied under such a scenario *assuming 100% harvest efficiency and no other constraints during biomass recovery.*

Table 5.7. Mixed-crop scheme Scenario 6

Ontario Regions	**10% Misc.**	**10% SG**	**60% HBS**	**20% Poplar**	**Total**
Southern	1,850,476	1,084,045	10,185,556	4,434,544	17,554,621
Western	1,587,274	949,674	8,792,830	3,876,638	15,206,416
Central	624,634	386,845	3,506,450	1,447,416	5,965,345
Eastern	913,215	552,894	5,089,587	2,009,852	8,565,548
Northern	64,690	41,076	-	-	105,766
Ontario Total	5,040,289	3,014,534	27,574,423	11,768,450	**47,397,696**

It must however be noted that yields of all agricultural crops can vary +/-30% as a result of normal changes in weather conditions (UWO Report, 2009). Thus, a sensitivity analysis of +/-30% can be performed on the yields used in this study. The scope of our study however does not warrant such an analysis. Suffice to say that possible biomass supply in Ontario could have a very wide range depending on the energy crop type, the percentage tillable land use, biomass yields in the different land classes, and whether the crops are grown in mixed schemes or as mono-crops in each region. For example, if grown alone across all tillable land classes, over 51 million tDM of Miscanthus or 31 million tDM of switchgrass can be supplied annually assuming there is 100%

recovery during spring harvest; if grown in mix-crop schemes, the annual supply could range between 9.4 million tDM and 50 million tDM.

CHAPTER 6: Summary and Conclusions

The primary objective of this study is to provide a global literature review on all essential agronomic activities related to the production of five energy crops that have potential to be grown on a large scale in Ontario. The selected energy crops include Miscanthus, switchgrass, reed canarygrass, high-biomass sorghum and hybrid poplar. The review also includes biomass densification and processing technologies, environmental issues related to energy crop production, issues associated with accessing biomass plant source materials, and the potential total supply of the selected energy crops across Ontario.

Unlike field crops such as soybean, wheat and corn, biomass crops lack long-term yield data for Ontario. The review however indicates that research on production and management technologies of energy crops are being stepped up globally and reports and published work on some selected energy crops, especially Miscanthus and switchgrass, are being released on more frequent basis. For example, a very recent report offered as a presentation by Mississippi State University (MSU) indicates that a newly certified strain of giant miscanthus (Miscanthus x giganteus) called ***"Freedom"*** exhibits very desirable qualities and characteristics that are superior to the conventional type. Such superior qualities include lower Chlorine (Cl) content (<80 ppm); increased heating value; lower moisture content at harvest (12%); and 3-5 times the yield of switchgrass and double the yield of current Miscanthus types.

Of all the five crops reviewed, Miscanthus appears to be the most promising energy crop across Ontario as can be inferred from the constructed ***selection matrix***. For some of the other crops, little or no information is available on a number of the attributes we reviewed. For example, not much can be found in the literature on the agronomics and pre-processing technologies of Reed canarygrass (RCG) and high-biomass sorghum (HBS) across the province; there is little or no information on the yields, harvesting practices, response to agro-chemicals or processing technologies of RCG. Other promising energy crops such as Giant Reed (*Arundo donax L),* Hemp

(Cannabis sativa) and Jerusalem artichoke *(Helianthus tuberosus* L) should be considered in future studies. Large-scale production of these crops in Ontario would require more strategic research, transparent government energy policies, demonstration farms, and the establishment of densification technologies across the province.

Recycling of ash to agricultural and forest land could return nutrients to the soil and could contribute to the sustainable use of biomass for power generation. Although this practice is already being implemented to some extent in some European countries such as Sweden, Finland, Austria and Germany, it is currently non-existent in Canada. Several factors could affect the ash quality of herbaceous biomass, namely (1) plant type and species, (2) plant fractions (i.e. stems versus leaves), (3) harvest time, (4) handling and storage, and (5) pre-processing. Of these factors, the manipulation of harvest time (e.g. delayed harvesting) that results in field leaching of undesirable chemical elements in biomass (except for silicates and N in RCG) is being seriously promoted in Canada. However, delayed harvest alone does not guarantee quality standards; delayed harvest can also have important tradeoffs, such as a high loss of plant matter (which reduces yields considerably) or an increase in total ash (due to losses of organic matter). Research into alternative pre-processing techniques to leach out inorganic constituents from biomass without sacrificing biomass yields and/or quality is therefore warranted.

In general, agricultural biomass may be subjected to various densification processes. Our review indicates that mechanical densification products such as *bales, pellets, briquettes, pucks and cubes* are applicable to the Ontario condition. Currently, bales and pellets are the only known established densified products in Ontario. However, little information is available on the best technologies suitable for each particular biomass source. Torrefaction, a processing technology, is used to improve the properties of biomass in relation to thermochemical processing techniques for energy generation. A major advantage of torrefaction is that it can convert biomass feedstocks which have non-uniform qualities into more uniform materials. However, torrefaction does not address the issues related to biomass chemical properties such as ash content and composition that negatively affect the performance of combustion processes and costs. *Bio-char*, originating from *fast pyrolysis'*, can be used within the process to provide process energy, or used as a soil conditioner. The review also identified farm-level management practices that may be used to improve biomass quality better combustion; such practices/strategies include crop selection, modifying growing conditions, plant fractionation during harvesting, manipulation of harvesting time and minimizing soil contamination.

Process-chain-analysis (PCA*), carbon footprint, water footprint, energy balances, carbon offset generation, soil erosion, phytoremediation and biodiversity* are examples of potentially significant environmental issues that may impact energy crop production. The quantification and discussion of these environmental issues for each energy crop is however beyond the scope of this study. Furthermore, the literature lacks all the necessary data and analyses required. A full assessment of each of the environmental issues requires a comprehensive life cycle analysis (LCA). There is therefore an urgent need to initiate LCA studies on each and every potential energy crop to provide systematic inventory and impact assessment of the environmental implications throughout its life cycle.

The principal aim of improving and selecting planting materials is to boost biomass yields, to improve resistance to both biotic and abiotic stresses and to enhance the feedstock quality for producing power and electricity**.** A key to the appropriate selection of energy lies with the planting materials to use. The technical development, sourcing and use of bioenergy crop planting materials however entail legal and propriety issues related to intellectual property rights, seed technology patents, licensing agreements, contracts and royalties. For example, ***"the Ceres Seed Use Agreement"*** binds the seed purchaser with the terms and conditions in the Agreement. Currently, Miscanthus rhizomes procured from ***New Energy Farms*** have no onward royalties and do have unencumbered use; similarly, switchgrass seeds purchased from ***Ernst Seed Company*** can be planted and the seeds saved for use in subsequent years. However, as new energy planting materials are developed through advances in biotechnology, new legal issues will emerge regarding the use of such biotech materials, and non-compliance of the laws could adversely impact both biomass producers and biomass end-users. To avoid any infringement, all stakeholders would have to develop a workable approach to keep abreast with newly developed planting materials and processes.

Based on available tillable land and productivity of the land classes under Ontario conditions, Ontario is capable of producing millions of tonnes of energy crop biomass annually. In this study, it was assumed there is no restriction on the conversion of any land class (Classes 1-5 lands) to energy crop production, and that the proportions of land classes that would be allocated to production would be dictated by economic considerations. It is also assumed that biomass productivity (yield/land area) on *"high-valued lands"* (Classes 1, 2 and 3 lands) is higher than that on "*marginal lands" (Classes 4 and 5 lands)*. Our analysis indicates that even if only 5% of land classes is used to produce Miscanthus across Ontario, we could obtain 2.5 million tDM biomass annually, assuming there is 100% recovery during harvesting; if the biomass originates from switchgrass, about 1.5 million tDM would be obtained. The amounts for reed canarygrass, high-biomass sorghum and poplar are 1.9, 2.3 and 2.9 million tDM, respectively. Mixed-crop scenarios involving the use of our 5 selected energy crops grown in combinations on only portions of tillable land across Ontario could produce substantial amounts of biomass.

REFERENCES

Acaroglu, M. and A.S. Aksoy 1998. Third year growing results of C4 energy plant *Miscanthus sinensis* in producing energy from biomass. pp. 758_759. In *Biomass for Energy and Industry,* Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpar, Germany.

Adler P.R., M.A. Sanderson, A.A. Boateng, P.J.Weimer and J.G. Hans-Joachim. 2006. Biomass yield and biofuel quality of switchgrass harvested in fall or spring. Agron. J. 98:1518–1525.

Adler, P. R., S. J. Del Grosso, and W. J. Parton. 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications 17:675–691.

Aitchison EW, Kelley SL, Alvarez PJJ, Schoor JL. 2000. Phytoremediation of 1,4-dioxane by hybrid poplar trees. Water Environ Res 2000;72:313–21.

Anderson E. K, T.B. Voigt G.A. Bollero, A.G. .Hager 2010. *Miscanthus* x *giganteus* response to pre-emergence and post-emergence herbicides. *Weed Technol.* 24(4) 453–460 (2010).

Anderson E., R. Arundale, M. Maughan, A. Oladeinde, A. Wycislo, and T. Voigt. 2011. Growth and Agronomy of Miscanthus x giganteus for biomass production. Biofuels 2 (2): 167-183.

Atkinson C.J. 2009. Establishing perennial grass energy crops in the UK: A review of current propagation options for Miscanthus. Biomass and Bioenergy 33, 752–759.

Aronsson, P.G., and L.F. Bergström, 2001. Nitrate leaching from lysimeter-grown short-rotation willow coppice in relation to N-application, irrigation and soil type. Biomass and Bioenergy 21: 155-164.

Association of Official Seed Analyses (AOSA) 1998. Rules for seed testing, AOSA, Beltsville .

Bakker R.R. and B.M. Jenkins. 2003. Feasibility of collecting naturally leached rice straw for thermal conversion. Biomass and Bioenergy. **25**:597–614.

Bakker R.R. et al, 2004. Biomass and Bioenergy 25:597-614.

Barkley, B.A. 1983. A silvicultural guide for hybrid poplar in Ontario. Ontario Ministry Natural Resources Publ #5093 35pp.

Baxter, L.L., T.R. Miles, T.R. Miles Jr, B.M. Jenkins, T. Milne and D. Dayton *et al.*, The behavior of inorganic material in biomass-fired power boilers: field and laboratory experiences, *Fuel Processing Technology* **54** (1998), pp. 47–78.

Beale C.V., D.A. Bint, and S.P. Long 1996. Leaf photosynthesis in the C-4-grass Miscanthus giganteus, growing in the cool temperate climate of southern England. Journal of Experimental Botany 47, 267–273.

Bergman, P, et al. 2005**.** *Torrefaction for entrained-flow gasification of biomass.* www.ecn.nl/biomass ECN-C--05-067.

Bergman, P. J. and Kiel, J. 2005. *Torrefaction for Biomass Upgrading.* ECN. November 2005. www.ecn.nl/biomass . ECN-RX--05-180.

Bergmann P.C.A., 2005, Combined torrefaction and pelletisation, *Energy Research Centre of* bioenergy feedstock. *Biofuels, Bioproducts and Biorefining* 1(2): 147-157.

Blanco-Canqui, H. 2010. Energy crops and their implications on soil and environment. Agron. J. 102:403-419.

Boerrigter H., Kiel J. and Bergmann P., 2006, Biomass pre-treatment by torrefaction, Energy Boerrigter, H (ECN**).** *Biomass Pretreatment by Torrefaction.* 3-5 April 2006. Third Thermalnet Meeting, Lille, France. available from: http://**www**.thermalnet.co.uk/docs/report_cofiring_lille_web.pdf .

Boysen, B. and S. Strobl. 1991. A growers guide to hybrid poplar. Ontario Ministry of Natural Resources, Toronto, Ontario, Canada. 148 pp.

Bridgwater**, A V.** *The future for biomass pyrolysis and gasification: status, opportunities and policies for Europe.* s.l: PyNe, November 2002. available from: http://ec.europa.eu/energy/res/publications/doc1/report_p536_v2.pdf . Contract No: 4.1030/S/01-009/2001.

Buhler, D. D., D.A. Netzer, D.E. Riemenschneider, and R.G. Hartzler, 1998. Weed management in short rotation poplar and herbaceous perennial crops grown for biofuel production. Biomass and Bioenergy 14, 385–394.

Bullard M. and P. Metcalfe. 2001. Estimating the energy requirements and CO_2 emission from production of the perennial grasses Miscanthus, switchgrass and reed canary grass. ADAS Consulting Ltd. URN 01/797, DTI (2001).

Bullard, M. J., P.M.I. Nixon, J.B. Kilpatrick, M.C. Heath, and C.S. Speller 1995. In Principles of Weed Control in Miscanthus spp. under Contrasting Field Conditions Paper presented at the Brighton Crop Protection Conference—Weeds, Brighton, UK.

Burken JG, Schnoor JL. 1997. Uptake and metabolism of atrazine by poplar trees. Environ Sci. Technol. 31:1399–406.

Burvall J, 1997. Influence of harvest time and soil type on fuel quality in reed canary grass (*Phalaris arundinacea* L.). Biomass and Bioenergy **12**:149–154.

Butler T. and B. Bean. 2002. Forage sorghum production guide. Texas Ag Exp Stn Stephenville. www.tamu.edu/~butler/foragesoftexas/pasture/forage%20sorghum%20temp.pdf .

Callan, B. 1998. Diseases of *Populus* in British Columbia : A diagnostic manual . Canadian For Service, Victoria, B.C. 155 pp.

Callan, B. 1998. Diseases of *Populus* in British Columbia : A diagnostic manual . Canadian For. Service, Victoria, B.C. 155 pp.

Carlson IT, Oram RN, Surprenant J. 1996. Reed canarygrass and other Phalaris species. p. 569–604. In: LE Moser, DR Buxton, MD Casler (eds) Cool-season forage grasses. Agron. Monogr. 34. ASA, CSSA, and SSSA, Madison, WI

Carlson, I.T., W.F. Wedin F.W. Schaller, and C.D. Hutchcroft. 1978. Vantage—a new reed canarygrass variety. Iowa State Univ Ext Serv Publ Pm-835.

Carroll A., Somerville C .2009. Cellulosic biofuels. Annual Review of Plant Biology, 60, 165–182.

Casler, D.C., J.H Cherney and E.C. Brummer. 2009. Biomass Yield of Naturalized Populations and Cultivars of Reed Canary Grass. Bioenerg. Res. 2: 165-173.

Casler, M.D., K.P. Vogel, C.M. Taliaferro, and R.I. Wynia. 2004. Latitudinal adaptation of switchgrass populations. Crop Sci. 44:293-303.

Caslin, B., J. Finnan, and A. McCracken. 2010. Miscanthus Best Practice Guidelines. http://www.teagasc.ie/publications/2010/20100916a/MiscanthusBestPracticeGuide2010.pdf

Cassida K.A., W.R. Ocumpaugh, and W.J. Grichar 2000. Using herbicides for improving establishment of switchgrass, in *Proceedings American Forage Grassland Council*. Madison, WI, July 16–19, Georgetown, TX, pp. 196–200.

CERES, 2010. Managing High-Biomass Sorghum as a Dedicated Energy Crop. Blade Energy Crops.

Cherney JH, Johnson KD, Volenec JJ, Greene DK (1991) Biomass potential of selected grass and legume crops. Energy Sources 13:283–292.

Cherney, J,H; Johnson, K,D; Volence, J,J; Anliker, K,S 1998. Chemical composition of Herbaceous grass and Legume Species grown for maximum biomass Production, 1988, Biomass, 17, 215-238.

Cherney, J.H., D.J.R. Cherney and M.D. Casler. 2003. Low-intensity harvest management of reed canarygrass. Agron. J. 95:627-634.

Chisholm C.J., 1994. Reed Canary Grass. In: Towards a UK Research Strategy for Alternative Crops. Silsoe Research Institute.

Clifton-Brown J. and I. Lewandowski.2002. "Screening *Miscanthus* genotypes in field trials to optimize biomass yield and quality in Southern Germany." European Journal of Agron.16:97-110.

Clifton-Brown J., I. Lewandowski, B. Andersson, G. Basch, D. Christian, J. Kjeldsen, U. Jorgensen, J. Mortensen, A. Riche, K-U. Schwarz, K. Tayebi and F. Teuxeira. 2001. "Performance of 15 *Miscanthus* Genotypes at Five Sites in Europe." European Journal of Agronomy 93:1010-1019.

Clifton-Brown, J. C. and I. Lewandowski, I. 2000a. Overwintering problems of newly established Miscanthus plantations can be overcome by identifying genotypes with improved rhizome cold tolerance. The New Phytologist 148, 287–294.

Clifton-Brown, J. C. and I. Lewandowski, I. 2000b. Water use efficiency and biomass partitioning of three different Miscanthus genotypes with limited and unlimited water supply. Annals of Botany 86:191–200.

Clifton-Brown, J. C., I. Lewandowski and S. Schneider, 1998. Establishment of 15 Miscanthus genotypes in Southern Germany. In Biomass for Energy and Industry. Proceedings of the 10th European Biomass Conference, Wu¨rzburg, Germany, pp. 926–929. C.A.R.M.E.N. Publishers, Rimpar, Germany.

Clifton-Brown, J. C., I. Lewandowski, B. Andersson, G. Basch, D.G. Christian, J.B. Kjeldsen, K-U. Schwarz, K. Tayebi, and F. Teixeira, F. 2001. Performance of 15 Miscanthus genotypes at five sites in Europe. Agronomy Journal 93, 1013–1019.

Chiaramonti, D, Oasmaa, A and Solantaust, Y**. 2005.** *Power generation using fast pyrolysis liquids from biomass.* Technical Research Centre of Finland (VTT), P.O.Box 1601, FIN-02044 VTT, Finland. July 2005. Available from: http://www.combio-project.com/download/PDF/Power_generation_using_fast_pyrolysis_liquids_from_biomass.pdf

Chisholm C.J. 1994. Reed Canary Grass. In: Towards a UK Research Strategy for Alternative Crops. Silsoe Research Institute).

Christian D.G., H.W. Elbersen, N. El Bassam. 2003. In: FAIR 5-CT97-3701. Switchgrass (*Panicum virgatum L*.) as an Alternative Energy Crop in Europe Initiation of a Productivity Network (ed.Elbersen W), pp. 72–92. EU,Wageningen, http://www.switchgrass.nl/.

Christian, D.G. and A.B. Riche 1998. Nitrate leaching losses under Miscanthus grass planted on a silty clay loam soil. Soil Use and Management 14:131-135.

Christian, D.G., A.B. Riche, and N.E. Yates. 1997. Nutrient requirement and cycling in energy crops. In: N. El Bassam, R.K. Behl and B. Prochnow, Editors, Sustainable agriculture for food, energy and industry, James & James (Ltd), London (1997), pp. 799–804.

Christian, D. G. and E. Haase. 2001. Agronomy of Miscanthus. In Miscanthus for Energy and Fibre, (M. B. Jones and M. Walsh, eds.), pp. 21–45. James & James, London.

Christian, D. G., M.J. Bullard, and C. Wilkins, C. 1997. The agronomy of some herbaceous crops grown for energy in southern England. Aspects of Applied Biology, Biomass and Energy Crops 49, 41–52.

Christian, D. G., A.B. Riche, and N.E. Yates. 2008. Growth, yield and mineral content of Miscanthus x giganteus grown as a biofuel for 14 successive harvests. *Industrial Crops and Products* 28: 320–327.

Colley, Z., Fasina, O.O., Bransby, D., Lee, Y.Y., 2006. Moisture effect on the physical characteristics of switchgrass pellets. Trans. ASABE 49 (6), 1845–1851.

De Oliveira, Marcelo E. Dias de, Burton E. Vaughan & Edward J. Rykiel Jr. 2005. "Ethanol as Fuel: Energy, Carbon dioxide Balances, and Ecological Footprint." BioScience Vol. 55 No. 7, July 2005]. Table 3.1.3.1

DeBell, D.S. and C.A. Harrington 1997. Productivity of *Populus* in monoclonal and polyclonal blocks at three spacings. Can J. For Res 27:978-985.

DEFRA. (Department for environment, Food and Rural Affairs, UK) 2007. Analysis of the UK Potential for Combined Heat and Power. *www.defra.gov.uk.* [Online] October 2007. [Cited: April 22, 2008.] http://www.defra.gov.uk/corporate/consult/carbon-reduc/consultation.pdf

DEFRA. 2005. *Biomass Task Force: Report to Government* [Online] October 2005. [Cited: April 29, 2008.] http://www.defra.gov.uk/farm/crops/industrial/energy/biomass-taskforce/pdf/btf-finalreport.pdf .

DEFRA, 2001. http://www.defra.gov.uk/evidence/statistics/foodfarm/farmmanage/fbs/published-data/farmaccounts/2007/index.htm

Del Grosso, S. J., W. J. Parton, A. R. Mosier, M. D. Hartman, J. Brenner, D. S. Ojima, and D. S. Schimel. 2001a. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. Pages 303–332 *in* M. Schaffer, L. Ma, S. Hansen, editors. Modeling carbon and nitrogen dynamics for soil management. CRC Press, Boca Raton, Florida, USA.

Demchik, M. et al 2002. Hybrid poplars as an alternative crop. Univ Minnesota Extension National Resources Special Report NRS-2. 7 pp.

Demirbas, A. 1997. Calculation of higher heating values of biomass fuels, Fuel 76 (5), 431-434.

Demirbas, A 2004. Combustion characteristics of different biomass fuels, Progress in energy and biomass combustion 2004, 30, 219-230.

Demirbas, K. and Demirbas, A. 2009. Technical assessment of different bio-renewable wastes into energy solutions by briquetting. Energy Educ. Sci. Technol. A 22:97–106.

Dickmann, D.I. et al. 2001. Poplar Culture in North America. NRC-Research Press. Ottawa, Canada. 397 pp.

Dobie, J.B. 1959. Engineering appraisal of hay pelleting. Agricultural Engineering. 40(2): 72-76.

DTI. 2003. *Our Energy Future - creating a low carbon economy*. Department of Trade and Industry (DTI) Publications Cm 5761, HMSO, London.

Edmundo, H. and S. Ulf. 1993. *Energy analysis of reed canary grass for solid fuel and ley for biogas.* [Report] http://pub.epsilon.slu.se/3871/

Elbersen, H.W., D.G. Christian, W. Bacher, E. Alexopoulou, V. Pignatelli and D. van den Berg. 2001. The European Switchgrass Project. In: S. Kyritsis, A.A.C.M. Beenackers, P. Helm, A. Grassi and D. Chiaramonti, Editors, *Biomass for Energy and Industry: Proceedings of the First World Conference, Sevilla, Spain, 5–9 June 2000*, James & James (Science Publishers) Ltd., London (2001), pp. 202–205.

Elbersen, H.W. and R. Bakker, 2003. Switchgrass as an alternative energy crop, Agrotechnology & Food Innovations, the Netherlands. http://www.switchgrass.nl/summary.htm**.**

Elbersen H.W. et al, 2002. Switchgrass as an alternative energy crop in Europe, Final report FAIR 5-CT97-3701. www.switchgrass.nl

Elsayed, M.A., R. Matthews, N.D. Mortimer. 2003. Carbon and energy balances for a range of biofuel options. URN 03/086. DTI; 2003.

Evans, G. 2008 *International Biofuels Strategy Project. Liquid Transport Biofuels - Technology Status Report.* s.l. : NNFCC, Nov 2007. Available from: http://www.nnfcc.co.uk/metadot/index.pl?id=6597;isa=DBRow;op=show;dbview_id=2539 . NNFCC 08-017.

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare, and D. M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. Science **311**:506–508.

Frank, A. B., Berdahl, J. D., Hanson, J. D., Liebig, M. A., and Johnson, H. A. 2004. Biomass and carbon partitioning in switchgrass. *Crop Sci.* **44**: 1391–1396.

Garten, C. T., and S. D. Wullschleger. 1999. Soil carbon inventories under a bioenergy crop (switchgrass): measurement limitations. *J. Environ. Qual.* 28:1359–1365.

Garten, C. T., and S. D. Wullschleger. 2000. Soil carbon dynamics beneath switchgrass as indicated by stable isotope analysis. *J. Environ. Qual.* 29:645–653.

Girouard, P. and R. Samson. 1996. Evaluation of conventional haymaking equipment for spring harvesting switchgrass. REAP-Canada report prepared for Domtar Inc., Noranda Inc. and Natural Resources Canada. Ottawa, Ontario. 12 pp.

Girouard, P. and R. Samson. 2000. *The potential role of perennial grasses in the pulp and paper industry. Making a case for agri-fibres.* Pulp and Paper Canada. 101:10: p. 53-55.

Goel, H.K. R. Eisner, G. Sherson, T. Radiotis, and J. Li. 1998. "Switchgrass: a Potential Pulp Fibre Source". In *Proceedings of the 84th Annual Meeting, Technical Section, Canadian Pulp and Paper Association*. Montreal. January 1998. Pp. B109-B114Hipple 2002.

Goudriaan, F. 2008. *HTU-Diesel from Wet Waste Streams.* May 2008. Symposium Neue Biokraftstoffe, Berlin. available from: http://www.fnr.de/neue-biokraftstoffe/.

Grigal, D. F., and Berguson, W. E. 1998. Soil carbon changes associated with short-rotation systems. *Biomass Bioenergy* **14**: 371–377.

Hadders G. and R. Olsson. 1997. Harvest of grass for combustion in late summer and in spring. Biomass Bioenergy. 12: 171-175.

Hall, M. H. 2010. Reed Canarygrass. Agronomy Facts 26. http://pubs.cas.psu.edu/freepubs/pdfs/uc089.pdf

Hallam AI, Anderson C and Buxton DR. 2001. Comparative economic analysis of perennial, annual and intercrops for biomass production. *Biomass Bioenergy* **21:**407–424 (2001).

Hansen, E. A. 1993. Soil carbon sequestration beneath hybrid poplar plantations in the north central United States. *Biomass Bioenergy* **5**: 431–436.

Hansen, E.A. 1983. Intensive Plantation Culture: 12 Years Research. USDA Forest Service North Central Forest Experiment Station General Tech Report NC-91. 155 pp.

Hartmann, H. 1998. Influences on the quality of solid biofuels—causes for variations and measures for improvement. In: H. Kopetz, T. Weber, W. Palz, P. Chartier and G.L. Ferrero, Editors, *Biomass for Energy and Industry*, CARMEN, Würzburg, Germany (1998), pp. 184–187.

Hansen, E.A. 1994. A guide to determining when to fertilize hybrid poplar plantations. USDA North Central Forest Experiment Station. Res Paper NC-319. 7 pp.

Hansen, E.A., et al. 1993. Guidelines for establishing poplar plantation in the North-Central US. USDA Forest Service. North Central Forest Experiment Station. Res Note NC-363.

Heller, M. C., G. A. Keoleian, and T. A. Volk. 2003. Life cycle assessment of a willow bioenergy cropping system. Biomass Bioenergy **25**:147–165.

Heaton, K. K. Moore, M. Sala-Fernandez, B. Hartzler. M. Liebman and S. Barnhart. 2010. Giant Miscanthus for Biomass Production. Iowa State University, University extension. http://www.extension.iastate.edu/Publications/AG201.pdf

Heaton E., J. Clifton – Brown, T. Voigt, M. Jones, and S. Long. 2003. *Miscanthus* for renewable energy generation: European Union experience and projections for Illinois. Mitigation and Adaptation Strategies for Global Change 9: 433-451.

Hiler E. 1989. Advanced Concepts in Biomass Production and Biological Pretreatment. TAES progress report to Gas Research Institute.

Himken M., J. Lammel, D. Neukirchen, U. Czypionka and H-W. Olfs. 1997. Cultivation of *Miscanthus* under West European conditions: Seasonal changes in dry matter production, nutrient uptake and remobilization. Plant and Soil 189:117-126.

Hoskinson, R.L., D.L. Karlen, S.J. Birrell, C.W. Radtke, and W.W. Wilhelm. 2007. Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. Biom. Bioenergy 31:126–136. http://users.ox.ac.uk/~kebl2245/Final_Report.pdf

Huisman. W., P.Venturi, and J. Molenaar. 1997. Costs of supply chains of Miscanthus Giganteus. Industrial Crops and Products, 6 (3,4): 353-367.

Hodkinson, T. R., Chase, M. W. and Renvoize, S. A. (2001). Genetic resources of Miscanthus. Aspects of Applied Biology 65, 239–248.

ISO International Organization for Standardization). 2006a. Environmental management -- Life cycle assessment -- Requirements and guidelines. http://www.iso.org/iso/catalogue_detail?csnumber=38498

Jenkins, B.M., R.R. Bakker and J.B. Wei. 1996. On the properties of washed straw. Biomass and Bioenergy 10(4):177-200.

Jensen, P.A., B. Sander and K. Dam-Johansen. 2001. Removal of K and Cl by leaching of straw char, *Biomass and Bioenergy* **20**(6): 447–457.

Jorgensen U. 1997. Genotypic variation in dry matter accumulation and content of N, K and Cl in *Miscanthus* in Denmark. Biomass and Bioenergy 12: 155-169.

Isebrands, J.G. 2007. Best Management Practices Poplar Manual For Agroforestry Applications in Minnesota http://www.extension.umn.edu/distribution/naturalresources/00095.html.

Isebrands, J.G. and D.I. Dickmann 2002. Environmental benefits of poplar culture. *In* Dickmann, D.I. et al (eds) Poplar Culture in North America. NRC Research Press, Ottawa, Canada. p. 207-218.

Isebrands, J.G. et al. 1979. Integrated utilization of biomass: A case study of short rotation intensively cultured *Populus* raw material. Tappi 62: 67-70.

Jankauskas B., Jankauskiene G. 2003. Tillage erosion as a predictor of runoff erosion on cultivated slopes. In: M. Bel, J. Benites, B. Boydel et al. (eds.), Soil Management for Sustainability. The University of Queensland, Brisbane. p 589-595.

Jannasch, R., Quan, Y., Samson, R., 2001. A Process and Energy Analysis of Pelletizing Switchgrass. Final Report, Natural Resources Canada.

Jarecki, M. and R. Lal. 2003. Crop management for soil carbon sequestration. Critical Reviews in Plant Sciences January 1, 2003.

Jasinskas, A. A. Zaltauskaset and A. Kryzeviciene. 2008. The investigation of growing and using of tall perennial grasses as energy crops. Biomass Bioenergy 32: 981-987.

Jenkins, B.M, L. L. Baxter, T.R Miles Jr., J.R. Miles. 1998. Combustion properties of biomass, Fuel Process Technology.

Johnson J.M.F., M.D. Coleman, R.W. Gesch, A.A. Jaradat, R. Mitchell, D.C. Reicosky and W.W. Wilhelm. 2007b. Biomass-bioenergy crops in the United States: A changing paradigm. *The Americas Journal of Plant Science and Biotechnology* 1:1-28.

Johnson J.M.F., N.W. Barbour and S.L. Weyers. *2007a.* Chemical composition of crop biomass impacts its decomposition. Soil Sci. Soc. Am. J. 71:155-162.

Johnson K**.** 2011. How to Plant Reed Canarygrass. http://www.ehow.com/how_7532018_plant-reed-canarygrass.html#ixzz1LZcGolpU**.**

Jørgensen, U., 2000. Har energiafgrøder en fremtid i Danmark? (Do energy crops have a future in Denmark?) DIAS Report No. 29. Markbrug. Danish Institute of Agricultural Sciences.

Kaliyan, N. and V. Morey. 2009. Factors affecting strength and durability of densified biomass products. Biomass Bioenergy. 33(3): 337-359.

Kaltschmitt. M. 1997. Biomass for energy in Europe—status and prospects In: M Kaltschmitt and AV Bridgwater, Editors, *Biomass gasification and pyrolysis—state of the art and future prospects*, CPL Scientific, Newbury, UK (1997).

Kassel A, Ghohal D, Goyal A. Phytoremediation of trichloroethylene using hybrid poplar. Physios Mol Biol Plants 2002;8:3–10.

Khanna, M., B. Dhungana, and J. Clifton-Brown. 2008. Cost of producing *Miscanthus* and switchgrass for bioenergy in Illinois". Biomass and Bioenergy 32:482-493

Kim S, Dale BE. 2005. Environmental aspects of ethanol derived from no-tilled corn grain: nonrenewable energy consumption and greenhouse gas emissions. Biomass Bioenergy 28:475–89.

Kimber C. 2000. Origins of domesticated sorghum and its early diffusion to India and China. In *Sorghum.* ed. by Smith CW and Frederiksen RA. John Wiley, New York, pp. 3–98.

Kinney, W.A. 1992. The role of *Salicaceae* species in windbreaks. For Chronicle 68:209-213.

Knudsen N.O. et al, 1998. Possibilities and evaluation of straw pretreatment, In: Biomass for Energy and Industry, Proceedings of the International Conference, Wurzburg, Germany.

Kort, J. and R.Turnock. 1996. Biomass production and carbon fixation by prairie shelterbelts. PFRA Shelterbelt Center, Indian Head, SK Rep. 95-6. 14 pp.

Kristensen, E.F., 2001.Teknik til høst af miscanthus (Technique for harvesting of miscanthus) (In Danish with English summary). DIAS Report No. 55. Markbrug. Danish Institute of Agricultural Sciences.

Lal, R. 2004. Carbon emission from farm operations. Environment International **30**:981–990.

Lal, R., Kimble, J. M., Follett, R. F., and Cole, C. V. 1999. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect.* Lewis Publishers, Boca Raton, FL, USA.

Landström S, Lomakka L, Andersson L (1996) Harvest in spring improves yield and quality of reed canarygrass as a bioenergy crop. Biomass BioEnergy 11:333–341.

Larsson, S. 2008. Fuel Pellet Production from Reed Canary Grass. Swedish University of Agricultural Sciences.

Lavergne S. and J. Molofsky. 2007. Increased genetic variation and evolutionary potential drive and success of an invasive grass. Proc. Natl Acad. Sci USA. 104:3883-3888.

Lawrence, J., Cherney, J., et al. Establishment and Management of Switchgrass. Agronomy Fact Sheet Series: Fact Sheet 20. Cornell University Cooperative Extension (US); [updated 2006; cited 2008 Dec 7] Available from:
http://www.nmsp.css.cornell.edu/publications/factsheets/factsheet20.pdf

Lewandowski, I. and A. Heinz. 2003. "Delayed harvest of miscanthus--influences on biomass quantity and quality and environmental impacts of energy production." European Journal of Agronomy 19(1): 45-63.

Lewandowski I., J. Clifton-Brown, J.M.O.Scurlock, W. Huisman.2000. “*Miscanthus*: European experience with a novel energy crop.” Biomass and Bioenergy. 19: 209-227.

Lewandowski, I., A. Kicherer, and P. Vonier. 1995. CO_2-balance for the cultivation and combustion of *Miscanthus. Biomass and Bioenergy* 8:81-90.

Licht, L.A. and J.G. Isebrands. 2004. Linking phytoremediated pollutant removal to biomass economic opportunities. Biomass Bioenergy 28:203-218.

Liebig M. A., M. R. Schmer, K. P. Vogel, and R. B. Mitchell. 2008. Soil Carbon Storage by Switchgrass Grown for Bioenergy. Bioenergy Res. 1:2 15–222.

Liebig, M. A., Johnson, H. A., Hanson, J. D., and Frank, A. B. 2005. Soil carbon under switchgrass stands and cultivated cropland. *Biomass Bioenergy* **28**: 347–354.

Lindvall, E. 1997. Breeding reed canarygrass as an energy or fibre crop by using local collected wild populations. In: Buchannan-Smith JG. Et al (eds) Proc. XV111 Intl. Grassl. Congr. Saskatoon, Sask., Canada Extension Service, pp 31-32.

Marland, G. and A. F. Turhollow. 1991. CO_2 emissions from the production and combustion of fuel ethanol from corn. *Energy* **16**(11-12):1307-1316.

Marten, G.C. and A.W. Hovin. 1980. Harvest schedule, persistence, yield, and quality interactions among four perennial grasses. Agron. J. 72:378-387.

Marten, G.C. C.E. Clapp and W.E. Larson. 1979. Effects of municipal wastewater effluent and cutting management on persistence and yield of eight perennial forages. Agron. J. 71:650-658.

Matthews, R.W. 2001. Modelling of energy and carbon budgets of wood fuel coppice systems, *Biomass Bioenergy* **21:**1–19.

Mccrillis RC, Watts, R. R., Warren, S. H. J. Effects of Operating Variables on PAH Emissions and Mutagenicity of Emissions from Woodstoves. Air Wastes 1992;42:691.

McCutcheon, S.C. and J.L. Schnoor. 2003. Phytoremediation: Transformation and Control of Contaminants. Wiley InterScience. Hoboken, N.J. 987 pp.

McKendry, P. 2002. Energy production from biomass (part 2): conversion technologies. Bioresource Technology 83: 47-54

McLaughlin, S. B., D. G. De La Torre Ugarte, C. T. GartenJr., L. R. Lynd, M. A. Sanderson, V. R. Tolbert, and D. D. Wolf. 2002. High-value renewable energy from prairie grasses. Environmental Science and Technology **36**:2122–2129.

Mirck, J. Isebrands, J. G. Verwijst, T. Ledin, S. 2005. Development of short-rotation willow coppice systems for environmental purposes in Sweden. *Biomass and Bioenergy 28: 219-228.*

McLaughlin, S.B. and M.E. Walsh, 1998. Evaluating environmental consequences of producing herbaceous crops for bioenergy Biomass and Bioenergy Vol. 14, No. 4, pp. 317-324.

Mekete, T., M.E. Gray, and T.L. Niblack 2009. Distribution, morphological description and molecular characterization of Xiphinema and Longidorous spp. associated with plants Miscanthus spp. and Panicum virgatum) used for biofuels. Global Change Biology. Bioenergy 1, 247–266.

Meridian Corp. 1986. Short rotation intensive culture of woody crops for energy: Principles and practices for the Great Lakes Region. Meridian Corp. Falls Church, VA. 85 pp.

Mertens, P. 1999. Environmental aspects of Sambro-Mense poplar culture. Biomass Bioenergy 16: 275-280.

Miles, T.R., J.T.R. Miles, L.L. Baxter, R.W. Bryers, B.M. Jenkins and L.L. Oden, Boiler deposits from firing biomass fuels, *Biomass & Bioenergy* **10** (1996), pp. 125–138.

Miller F.R., G.G. McBee, F.M. Hons and J.T. Cothren JT. 1989. Biomass production, quantity and quality, in *Advanced Concepts in Biomass Production and Biological Pretreatment.* ed. by Hiler E. Advanced Concepts in Biomass Production and Biological Pretreatment. TAES progress report to Gas Research Institute (1989).

Minnesota Department of Natural Resources/ Wes Min RC&D. 2004. Hybrid poplar handbook. Willow River, MN. 37 pp.

Mitchell et al. 2007. *A Foresighting Study into the Business Case for Pellets from Torrefied Biomass as a New Solid Fuel.* All Energy 2007. Available from http://www.all-energy.co.uk/UserFiles/File/2007PaulMitchell.pdf .

Monk R.L., F.R. Miller and G.G. McBee. Sorghum improvement for energy production. *Biomass* **6**:145–385 (1984).

Monti, A. N. Di Virgilio and G. Venturi. 2008. Mineral composition and ash content of six major energy crops. Biomass and Bioenergy. 32 (3): 216-223.

Morrison, S. and J. Molofsky. 1998. Effects of genotypes, soil moisture, and competition on the growth of an invasive grass, *Phalaris arundinacea* (reed canary grass). Can. J. Bot. 76: 1939-1946s

Moser, L.E. and K.P.Vogel. 1995. Switchgrass, Big Bluestem, and Indiangrass. *In:* An introduction to grassland agriculture. R. F. Barnes, D. A. Miller and C. J. Nelson (eds.). Forages, 5th ed. Vol.1, Ames, IA: Iowa University Press, pp. 409-420.

Moilanen, A., M. Nieminen, K. Sipila, and E. Kurkela. 1996. Ash behavior in thermal fluidized bed conversion processes of woody and herbaceous biomass. pp. 1227_1232. In *Biomass* *forEnergy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.

Naidu SL, Moose SP, Al-Shoaibi AK, Raines CA, Long SP (2003) Cold tolerance of C4 photosynthesis in Miscanthus×giganteus: adaption in amounts and sequence of C4 photosynthetic enzymes. Plant Physiology, 132, 1688–1697.

Netzer, D.A. et al. 2002. Growth, yield, and disease resistance of 7- to 12-year old poplar clones in North Central United States. USDA Forest Service, North Central Research Station GTR-NC-229. 33 pp.

Nikolaou K, Masclet, P., Mouvier G. 1984. Sources and chemical reactivity of polynuclear aromatic hydrocarbons in the atmosphere — A critical review. Sci Total Environ 1984;32:103.

Nordin, A. 1994. Chemical elemental characteristics of biomass fuels, Biomass and Bioenergy, 6(5): 339-347

O'Brien, T. R., L. E. Moser, R.A. Masters, and A.J.Smart. 2008. Morphological development and winter survival of switchgrass and big bluestem seedlings. Online. Forage and Grazinglands doi:10.1094/FG-2008-1103-01-RS.
http://www.plantmanagementnetwork.org/sub/fg/research/2008/seedling/

Oosten, C. 2006. Hybrid poplar crop manual for the prairie provinces. Saskatchewan Forest Centre, Prince Albert, SK and Poplar Council Canada, Edmonton, AB, Canada. Web publication. 10 MB.pdf.

Ostry, M. et al. 1989. A guide to insect, disease and animal pests of poplars. USDA Forest Service, Washington, D.C. Agriculture Handbook #677. 117 pp.

Ostry, M. et al. 1989. A guide to insect, disease and animal pests of poplars. USDA Forest Service, Washington, D.C. Agriculture Handbook #677. 117 pp.

Ostry, M.E. and H.S. McNabb, Jr. 1986. *Populus* species and hybrid clones resistant to *Melamspora*, *Marssonnia* and *Septoria.* USDA North Central Forest Experiment Station Res Paper NC-272. 7pp.

Pahkala K, M. Aalto, M. Isolahti, J. Poikola and L. Jauhiainen. 2008. Large-scale energy grass farming for power plants- a case study from Ostrobothnia, Finland. Biomass Energy 32: 1009-1015.

Pahkala K, M. Kontturi, A. Kallioinen, O. Myllymaki, J. Uusitalo, M. Siika-aho. 2007. Production of bioethanol from barley straw and reed canarygrass: a raw material study (pp 154–157). 15th Euro. Biomass Conf. and Exhibition, Berlin, Germany.

Pahkala K., T. Mela, H. Hakkola, A. Jarvi, and P. Virkajari. 1996. Production and use of agrifibre in Finland, Part1: Production of agrifibre: Agronomy varieties. Agric. Res. Centre of Finland, Jokioinen, Finland.

Pallardy, S.G. et al. 2003. Biomass production by two-year-old poplar clones on floodplain sites in the Lower Midwest, USA. Agroforestry Systems 59:21-26.

Pambudi, N.A. 2011. Upgrading Biomass by Torrefaction. http://EzineArticles.com/5283094.

Parrish, D. J., J.H. Fike, D.I. Bransby, and R. Samson, R. 2008. Establishing and managing switchgrass as an energy crop. Online. Forage and Grazinglands doi: 10.1094/FG-2008-0220-01-RV http://reap-canada.com/online_library/feedstock_biomass/5-Establishing%20and%20Managing%20Switchgrass%20as%20an%20Energy%20Crop%20_Parrish%20et%20al.%202008.pdf

Parrish, D.J. and Wolf, D.D., 1992. Managing switchgrass for sustainable biomass production. In: Cundiff, J.S., Editor, 1992. *Liquid Fuels from Renewable Resources. Proc. of an Alternative Energy Conf.*14–15 December 1992, Nashville, TN, Am. Soc. Agric. Engng, pp. 34–39.

Parrish, D.J., Wolf, D.D., Daniels, W.L., 1993. Perennial Species for optimum production of herbaceous biomass in the Piedmont. Management Study, 1987–1991. ORNL/Sub/5-27413/7. National Technical Information Service, US Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161, USA.

Paustian, K., J. Six, E. T. Elliott, and H. W. Hunt. 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry **48**:147–163.

Perttu KL, Kowalik PJ. Salix vegetation filters for purification of waters and soils. Biomass Bioenergy 1997;12:9–19.

Pedretti F.E., Toscano G, Duca D, Pizzi A, and Riva G. 2010. Effects of the Quality of the Biomass on Combustion Emissions of Stoves and Small Boilers. *International Conference Ragusa SHWA2010 - September 16-18, 2010 Ragusa Ibla Campus- Italy "Work Safety and Risk Prevention in Agro-food and Forest Systems"* 585

Perry, C.P. et al. 2001. Impacts of short rotation hybrid poplar plantations on regional water yield. For. Ecology Mgt. 143:143-151.

Perttu KL. 1999. Environmental and hygienic aspects of willow coppice in Sweden. Biomass Bioenergy 16:291–7.

Porter, C.I. 1996. An analysis of variation between upland and lowland switchgrass, Panicum Virgatum L. in central Oklahoma. Ecology 47:980-992.

Price, L. (2004). Identifying the yield potential of Miscanthus giganteus: An assessment of the spatial and temporal variability of M. giganteus biomass productivity across England and Wales. Biomass and Bioenergy 26, 3–13.

Price, L., Bullard, M., Lyons, H., Anthony, S. and Nixon, P., 2003, Identifying the yield potential of miscanthus x giganteus: An assessment of the spatial and temporal variability of M-x giganteus biomass productivity across England and Wales. *Biomass and Bioenergy*, 26, 3-13.

Pyter, R., Voigt, T., Heaton, E., Dohleman, F., and Long S., 2007. Giant Miscanthus: Biomass Crop for Illinois, *Issues in new crops and new uses*, J. Janick and A. Whipkey (eds.). ASHS Press, Alexandria, VA.

Ranney, J.W. et al. 1987. Hardwood energy crops: The technology of intensive culture. J.Forestry 85:17-28.

Reddy BVS and Reddy PS, Sweet sorghum: characteristics and potential. *Int Sorghum Millets Newslett* **44:**26–28 (2003).

Reumerman, P.J. 2002. Van den Berg D. Reduction of fouling, slagging and corrosion characteristics of miscanthus (the BIOMIS project) report. EC contract FAIR-98-3571, 2002.

Riemenschneider, D.E. et al. 2001. Poplar breeding and testing strategies in the North Central US: Demonstration of potential yield and consideration of future research needs. For Chronicle 77:245-253.

Robertson, G. P., E. A. Paul, and R. R. Harwood. 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. Science 289:1922–1925.

Rowe R. L., N.R. Street and G. Taylor. 2009. Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. Renewable and Sustainable Energy Reviews 13:271-290.

Rockwood, D.L. et al. 2004. Short rotation woody crops and phytoremediation: opportunities for agroforestry? Agroforestry Systems 61:51-63.

Rooney WL and Aydin S, The genetic control of a photoperiod sensitive response in *Sorghum bicolor* (L.) Moench. *Crop Sci* **39:**397–400 (1999).

Rooney, W. L., J.B. Bean and J. E. Mullet. 2007. Designing sorghum as a dedicated energy crop. http://onlinelibrary.wiley.com/doi/10.1002/bbb.15/abstract

Russelle, M.P., G.W. Randall, P.D. Clayton, M.A. Schmitt, L.J. Greub, C.C. Sheaffer, R.R. Kalton and D.H. Taylor. 1997. Reed canarygrass response to liquid dairy manure or fertilizer N.

Samson R. and B. Mehdi. 1998. "Strategies to reduce the ash content of perennial grasses"; Expanding Bioenergy Partnerships, Bioenergy 98, Great Lakes Regional Biomass Energy Program, Chicago, Illinois, pp. 1124-1131.

Samson, R. 2007. Switchgrass production in Ontario: A management guide. Online: Resource Efficient Agricultural Production (REAP)-Canada, Ste. Anne de Bellevue, Quebec.

Samson, R., P. Girouard, and B Mehdi 1999b. Establishment of commercial switchgrass plantations. Resource efficient Agricultural Production-Canada. Ste. Ann de Bellevue. Quebec.

Samson, R., P. Girouard, B. Mehdi. 1999. Establishment of commercial switchgrass plantations. Final report prepared for Domtar Inc., Noranda & Natural Resources Canada.

Samson, R.A. 2007. Resource Efficient Agricultural Production (REAP) – Canada. Revised from: Girouard, P., B. Mehdi, R. Samson and P. Blais, 1999. Joint publication by Resource Efficient Agricultural Production (REAP) – Canada and the Research and Technology Transfer Section of the Collège d'Alfred of the University of Guelph. ***http://www.reap-canada.com/library/Bioenergy/2007%20SG%20production%20guide-FINAL.pdf***.

Samson R. M. Drisdelle, L. Mulkins, C. Lapointe, and P. Duxbury. The use of switchgrass biofuel pellets as a greenhouse gas offset strategy. http://reap-canada.com/library/Bioenergy/14%20The%20Use%20of%20Switchgrass%20Biofuel%20Pellets%20as%20a%20Greenhouse%20Gas%20Offset%20Strategy.htm.

Sanderson, M. A., R. L. Reed, S. B. McLaughlin, S. D. Wullschleger, B. V. Conger, D. J. Parrish, D. D. Wolf, C. Taliaferro, A. A. Hopkins, W. R. Ocumpaugh, M. A. Hussey, J. C. Read and C. R. Tischler. 1996. Bioresource Technology56(1): 83-93.

Sartori, F., R. Lal, Rattan , M.H. Ebinger, and D.J. Parrish. 2006. Potential Soil Carbon Sequestration and CO2 Offset by Dedicated Energy Crops in the USA', Critical Reviews in Plant Sciences, 25: 5, 441-472.

Schlamadinger, B., and Marland, G. 1996. The role of forest and bioenergy strategies in the global carbon cycle. *Biomass Bioenergy* **10**: 275–300.

Schmidt, M.A. and G.W. Randall. 1993. Best management practices for nitrogen use in east-central and central Minnesota. Minnesota Extension Service, University of Minnesota, St. Paul, MN. AG-FO-6129-B. 3 pp.

Schwarz, H., P. Liebhard, K. Ehrendorfer and P. Ruckenbauer 1994. The effect of fertilization on yield and quality of Miscanthus sinensis 'Giganteus'. Industrial Crops and Products 2, 153–159.

Scurlock, J.M.O., 1998. *Miscanthus*: a review of European experience with a novel energy crop. ORNL/TM-13732.Oak Ridge National Laboratory, Oak Ridge, Tennessee. 26 pp.

Semere T. and F. Slater. 2005. The effects of energy grass plantations on biodiversity. B/CR/00782/00/00, URN 05/1307. DTI; 2005.

Shapouri, H., J. A. Duffield, and M. Wang. 2002. The energy balance of corn ethanol: an update. Agricultural Economic Report 813. U.S. Department of Agriculture, Washington, D.C., USA.

Shaw, M.D. and L.G. Tabil. 2007. Compression and relaxation characteristics of selected biomass grinds. Presented at the ASAE Annual International Meeting, June 17-20, 2007, Minneapolis, MN. ASAE Paper No. 076183. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659 USA.

Sheaffer, C.C. and G.C. Marten. 1995. Reed canarygrass. In: Barnes R.F., Miller D.A., Nelson C.J. (eds) Forages volume 1. An introduction to grassland agriculture. Iowa State University Press. Ames, pp 335-343.

Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelson. 2004. Energy and environmental aspects of using corn stover for fuel ethanol. Journal of Industrial Ecology **7**:117–146.

Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, and H. Shapouri. 1998. Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. NREL/SR-580-24089. National Renewable Energy Laboratory, Golden, Colorado, USA.

Shinners, K.J., G. C. Boettcher, R. E. Muck, P. J. Weimer, M. D. Casler. 2006. Harvest and storage of two perennial grasses as biomass feedstocks. Power & Machinery Division of ASABE in March 2010. Presented at the 2006 ASABE Annual Meeting as Paper No. 061012.

Six, J., R. T. Conant, E. A. Paul, and K. Paustian. 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil **241**:155–176.

Spath, P. L., and M. K. Mann. 2004. Biomass power and conventional fossil systems with and without CO_2 sequestration. Comparing the energy balance, greenhouse gas emissions and economics. NREL/TP-510-32575. National Renewable Energy Laboratory, Golden, Colorado, USA.

Stephens W, Hess T, Knox J. Review of the effects of energy crops on hydrology. NF0416. Cranfield University, MAFF; 2001.

Sladden, S.E., D.I. Bransby and G.E. Aiken. 1991. Biomass yield, composition and production cost for eight switchgrass varieties in Alabama. *Biomass and Bioenergy* **1** 2 (1991), pp. 119–122.

Smeets E.M.W., *I.M.* Lewandowski and A.P.C. Faaij.2000. The economical and environmental performance of *Miscanthus* and switchgrass production and supply chains in a European setting. Renewable & Sustainable Energy Reviews, 13, 1230–1245.

Sokhansanj S., S. Mani, A. Turhollow, A. Kumar, B. Bransby, L. Lynd, M. Laser. 2009. Large scale production, harvest and logistics of switchgrass (PANICUM VIRGATUM L.) – current technology and envisioning a mature technology. Biofuel, Bioproduct, Biorefinery 3:124-141.

Speller C S. 1993. The potential of growing biomass crops for fuel on surplus land in the UK. *Outlook on Agriculture* 22:23-29.

Stanley RL and Dunavin LS, Potential sorghum biomass production in North Florida, in *Biomass Energy Development*, ed. by Smith WH. Plenum Press, New York, pp. 217–226 (1986).

Stettler, R.F. et al. 1996. Biology of *Populus* and its Implications for Management and Conservation, NRC Research Press. Ottawa, Ontario, Canada. 539 pp.

Styles D., F. Thorne, M. Jones. 2008. Energy Crops in Ireland: An economic comparison of willow and *Miscanthus* production with conventional farming systems. Biomass and Bioenergy 32(2008): 407-421.

Styles, D. and M. B. Jones. **2007.** *Miscanthus* and willow heat production—An effective land-use strategy for greenhouse gas emission avoidance in Ireland? Energy Policy 36 (1): 97-107.

Summers M.D. et al, 2001. Properties of Rice Straw as Influenced by Variety, Season and Location, ASAE paper number 01-6078, ASABE, St. Joseph, MI, USA.

Swartz RC, Schults, D. W., Ozretich, R. J., Lamberson, J. O., Cole, F. A., Dewitt, T. H., Redmond, M. S., Ferraro, S. ΣPAH: a model to predict the toxicity of polynuclear aromatic hydrocarbon mixtures in field-collected sediments. EnvironToxicol Chem 1995;14:1977.

Tabil, Jr., L.G. 1996. Binding and pelleting characteristics of alfalfa. Unpublished Ph.D.

Tabil, Jr., L.G., S. Sokhansanj and R.T. Tyler. 1997. Performance of different binders during alfalfa pelleting. Canadian Agricultural Engineering 39 (1): 17-23.

Tabil, L., Jr., and S. Sokhansanj. 1996. Process conditions affecting the physical quality of alfalfa pellets. *Applied Eng. in Agric.* 12(3): 345-350.

Tahir M.H.N., M. D. Casler, K. J. Moore, and E. C. Brummer. 2011. Biomass Yield and Quality of Reed Canarygrass under Five Harvest Management Systems for Bioenergy Production. Bioenerg. Res. 4:111-119 http://www.springerlink.com/content/b677l7vt2785hj77/

Temmerman, M, F. Rabier, P.D. Jensen, H. Hartmann and T. Bohm. 2006. Comparative study of durability test methods for pellets and briquettes, *Biomass and Bioenergy* 30 (11) (2006), p. 964. *The Netherlands (ECN).*

Turn et al. 2008. Removal of inorganic constituents of fresh herbaceous fuels: processes and costs, Proceedings Third Biomass Conference of the Americas, Montreal.

Uemura, Y, Omar, W, Tsutsui, T; Subbarao, D, Yusup, S; Relationship between Calorific value and Elementary Composition of Torrefied Lignocellulosic Biomass, Journal of Applied Sciences, 2010, 10(24), 3250-3256

University of Western Ontario Report (UWO) Report. 2009. http://www.bicsarnia.ca/reports/uwo-report-1_layout-1.pdf

Uslu, A. 2005. *Pre-treatment technologies and their effects on the international bioenergy supply chain logistics. Technoeconomic evaluation of torrefaction, fast pyrolysis and pelletisation.* December 2005. Available from: http://www.chem.uu.nl/nws/www/publica/Studentenrapporten/Studentenrapporten2005/I2005-27.pdf .

Van Loo S., Koppejan J.. 2008. The handbook of biomass combustion and co-firing, Earthscan.

http://www.renewableenergyworld.com/rea/partner/earthscan/products/the-handbook-of-biomass-combustion-and-co-firing.

Venturi P., W. Huisman, J. Molenaar. 1998. Mechanization and Costs of Primary Production Chains for *Miscanthus* x *giganteus* in the Netherlands. Journal of Agricultural Engineering Research 69: 209-215Walsh and McCarthy 1998.

Vogel, K.P., J.J. Brejda, D.T. Walters and D.R. Buxton. 2002. Switchgrass biomass production in the Midwest USA: Harvest and nitrogen management. Agron. J.94:413-420.

Vogel, K.P. 1996. Energy production from forages (or American agriculture: back to the future). *J. Soil and Water Conserv. 51*:137–139.

Volk, T.A., Verwijst, T., Tharakan, P.J., Abrahamson, L.P. & White, E.H. 2004. Growing fuel: a sustainability assessment of willow biomass crops. *Frontiers in Ecology and the Environment*, 2: 411–418.

Wihersaari, M. 2005. Evaluation of greenhouse gas emission risks from storage of wood residue. Biomass and Bioenergy 285(5): 444–453.

Winkler, W. 2010. Briquetting Systems, New York.
Wrobel C, Coulman BE, Smith DL (2009) The potential use of reed canarygrass (*Phalaris arundinacea* L.) as a biofuel crop. Acta Agric Scand Sect B–Soil Plant Sci 59:1–18.

Wullscheleger, S.D., E.B. Davis, M.E.Borsul, C.A. Gunderson, and L.R. Lynd. 2010. Biomass production in Switchgrass across the United States: Database description and determinants of yield. Agron. J. 102 (4): 1158-1168.

Xiong, S., Q-G. Zhang, D-Y Zhangand R. Olsson. 2008. Influence of harvest time on fuel characteristics of five potential energy crops in northern China. Bioresource Technology. 99(3): 479-485.

Zan, C. S., Fyles, J.W., Girouard, P., and Samson, R. A. 2001. Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. *Agric. Ecosyst. Environ.* **86**: 135–144.

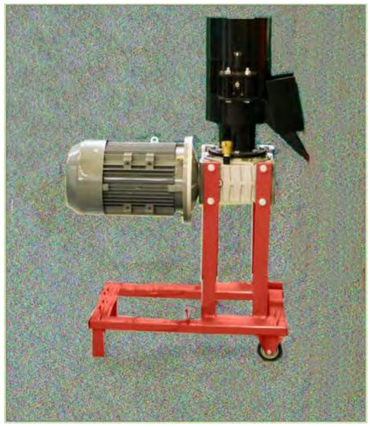
Zanzi, R, D. T. Ferro, A. Torres, P. B. Soler and E. Bjournbom. *Biomass Torrefaction.* Department of Chemical Engineering and Technology, Royal Institute of Technology. Stockholm, Sweden : s.n., undated. Available from: http://hem.fyristorg.com/zanzi/paper/zanziV2A-17.pdf.

Zenone, T., Facciotto, G., et al., 2004.SRF in Italy: the example of the Lombardy Region. 2nd World Conference on Biomass for Energy, Industry and Climate Protection, Rome, Italy, ETA Florence.

APPENDIX A1: : DENSIFICATION MACHINES/EQUIPMENT

PELLETIZING EQUIPMENT DETAILS

Name	Model Number	Picture	Feed	Technical Specifications/ Operating Method	Special Features	Price	Country of Origin	Web site
Pellet Mill	LM-772		Sawdust, Straw, Biomass, Paper	~ Requirements for the feed moisture level- Upto 12% ~ Pellet size - 3.5mm, 6mm or 8mm ~ Approximate space required - 4 Square Meter ~ Power for full unit - 19 kW 400V / 25A and 230V / 16A			Czech Republic	http://www.smallpelletmill.com/small-granulation-unit-pellet-mill-lm-772/

Pellet Mill	LM 2		Sawdust, Straw, Grass, Paper	~ Requirements for the feed moisture level- Upto 12% ~ Pellet size - 3.5mm, 6mm or 8mm ~ Approximate space required - 1 Square Meter ~ Power for full unit - 5 kW 400V / 25A	~ Easy to install, Operate and Store ~ Affordable ~ Industrial Quality Item	Czech Republic	http://www.smallpelletmill.com/small-pellet-mill-lm-2/
Ring Die	GC-MZLH-Series	 Wood Pelletizing Plant	Wood, Straw, other Biomass sources	~ Capacity ranges are from 200kgs to 3T per hour. ~ Positive direct gear drive provides a 98% energy transfer	The imported key elements are of high performance with long life and low maintenance cost.	China	http://woodpelletline.com/wood-pellet-plant.html

Pellet Mill	KMPM520			~ Capacity ranges from 0.5-3.5 (T/H) ~ Net Weight ranges from 1990 to 4900 kgs	Manufactured from the technical know how from Muench-edelstah GmbH in Germany		China	http://woodpelletline.com/kemc.pdf
Pellet Pros	PP 85		All Biomass (Softer woods)	~ Power: 220 V/ Single Phase / 60 Hz american motor, ~ Amp : 20 ~ Production Capacity 80 lb/hr		$ 1995.00 (USD)	USA	http://www.pelletpros.com/id68.html
Pellet Pros	PP 220		All Biomass and Softer woods	~ Power: 220 V/ Single Phase / 60 Hz american motor, ~ Amp : 25 ~ Production capacity: 110-220 lb/hr, ~ Hp : 5		$ 2395.00 (USD)	USA	http://www.pelletpros.com/id68.html

Pellet Pros	PP 600 A		All Biomass Products	~ Power: 220 V/ Single Phase / 60 Hz american motor, ~ Amp : 34 ~ Production Capacity: upto 600 lb/hr, ~ HP : 10	$ 4195.00 (USD)	USA	http://www.pelletpros.com/id68.html
Pellet Pros	PP 600 W		Only Wood Products	~ Power: 220 V/ Single Phase / 60 Hz american motor, ~ Amp : 34 ~ Production Capacity: upto 100 - 200 lb/hr, ~ Hp : 10	$ 4500.00 (USD)	USA	http://www.pelletpros.com/id68.html
Pellet Pros	PP 800			Power: 30 Hp Electric, Phase : 3 phase/ 60 Hz Production capacity: upto 800-1000 lb/hr	$ 7995.00 (USD)	USA	http://www.pelletpros.com/id70.html

Pellet Pros	PP 2800 J			Power: 30 Hp Electric, Phase : 3 phase/ 60 Hz Production capacity: upto 800 lb/hr	$ 11995.00 (USD)	USA	http://www.pelletpros.com/id70.html
Pellet Pros	PP 850 D		All Biomass Products	Power: 30 Hp Diesel, 2 Cylinder self contained/ Radiator w fan/ Electric start, Production capacity: upto 1000 lb/hr	$ 9995.00 (USD)	USA	http://www.pelletpros.com/id70.html
Pellet Pros	PP 650 D-2		All Biomass Products	Power : 15Hp Diesel/ Liquid cooled /Electric Start Production Capacity: 600 lb/hr	$ 3995.00 (USD)	USA	http://www.pelletpros.com/id70.html

Pellet Pros	PP-PTO		All Biomass Products	PTO speed: 540 RPM 6 Spilne 1 3/8" Shaft Hp: 25 Production Capacity: 300-600 lb/hr	$ 4300.00 (USD)	USA	http://www.pelletpros.com/id70.html
Wanda	SZLH 32 35		Biomass, Sawdust, Rice Husk			China	http://www.alibaba.com/product-gs/396048266/biomass_pellet_machine_SZLH32_35_with.html

Huizhou	HKJ-32		HKJ-32 biomass pellet machine, Yield: 300~500kg/h , Main motor power: 44kw , Particle Diameter: 6-8mm	. Extruding pressure reaches 50-100MPa		China	http://www.alibaba.com/product-gs/245879249/biomass_pellet_machine.html
Weifeng	MZLH508,420		Voltage: 3 Phase,380V,50HZ Type: Ring die and gear drive Pellet size: 6mm-12mm Length: 30mm-45mm Capacity:1-24t/h		US $5,750 - 29,21	China/Taiwan	http://www.alibaba.com/product-gs/430736623/industrial_biomass_pellet_making_machines.html

Youlong	SKJ3		Sawdust , rice husk, cotton stalk and all kinds of crop straw, home wastage,	Length: 2-15 mm		China	http://www.alibaba.com/product-gs/315384286/CE_approved_biomass_pelleting_machine.html
Wan Da	PM 300		Biomass, Sawdust,	Sawdust pellet capacity(kg/h): 200, Feedstuff pellet capacity(kg/h): 400, Pellet diameter(mm): 6-12	US $100 - 10,000	China	http://www.alibaba.com/product-gs/418369038/Hot_sale_biomass_pellet_machine.html

Passaro			Tree wastes, chilly waste, bamboo waste, sugarcane waste and all other wooden wastes.			India	http://www.alibaba.com/product-tp/112458751/Tractor_Mounted_Biomass_Pellet_Machine.html
Amisy	ZP-02		Straw ,rice hull, bamboo ends ,fibre and other agriculture waste from the farm	Capacity: 800-1200kg/h Diameter of the final product can be 6-33mm Density is 0.9-1.4kg/m3 Heat value :3500-5500calorie	US $7,000 - 10,000	China	http://www.alibaba.com/product-gs/275796251/biomass_pellet_machine_ZP_02.html

APPENDIX A2: BRIQUETTING EQUIPMENT DETAILS

Name	Model Number	Picture	Feed	Technical Specifications/ Operating Method	Special Features	Price	Country of Origin	Website
Roller Briquette Press	GCXM-1	 GCXM-15 Briquetting Press	Colour, black metallic mine powder, Coal Dust, Other Powdery material	Power : 5.5 kw, Producing Capacity : 1-2 TPH, Dia of Roller : 290 mm, Width of Roller : 200 mm, Weight : 560 kg,	Two Rollers Single Press		China	http://www.briquettepress.com/Roller-briquetting-presses.html
	Haiqi-HQ		All Biomass and straw	Materials kept dry when going into and coming out of the pellet making machine, (moisture of raw material≥13%). It is used with motor or diesel engine.	Density : 0.7-0.8, Ash Content =0.7% Calorie= 4500 J		China	http://www.alibaba.com/product-gs/423130427/Biomass_pellet_machine.html

Biomass Briquette Press	ZBJI		All Biomass	Output kg/h 80-120 Motor Power (kw) -11kw Electric heater (kw)-1.5kw*3pcs Weight(kg) -650kg Overall dimension(mm)-1780*750*1290 Size of finished products(dia)-30,40,50 mm	China	http://www.agico.com.cn/briquette-press/briquette-press.html
Biomass Briquette Press	ZBJII			Output kg/h-120-150 Motor Power (kw) -15kw Electric heater (kw)-1.5kw*3pcs Weight(kg) -650kg Overall dimension(mm)-1650*600*1260 Size of finished products(dia)-30,40,50 mm	China	http://www.agico.com.cn/briquette-press/briquette-press.html

	150						
Biomass Briquette Press	ZBJIII			Output kg/h 180-230 Motor Power (kw) -18.5kw Electric heater (kw)-2kw*3pcs Weight(kg) -900kg Overall dimension(mm)-1860*800*1360 Size of finished products(dia)-60,70,80,90,100 mm		China	http://www.agico.com.cn/briquette-press/briquette-press.html
Jutao	SKJ30-1B		Wood waste, branch, palm tree, bean straw, wheat straw, corn straw, cotton straw, rice straw, husk,	Power 30 kw, O/P (t/h) 0.8to1.2 Density(g/cm3) 0.8to1.2 Actual Power >22kw Dimensions 1800*900*1750	US $18,000 - 75,500	China	http://www.alibaba.com/product-gs/381222506/Biomass_briquette_machine.html

			cotton shell, peanut shell, rice shell, palm tree, coconut shell		
Hongzheng	SBJ-3150A		All Biomass	China	http://www.alibaba.com/product-gs/227130632/briquetting_machine_biomass_briquette_machine_briquette.html

Briquette Press biomass briquette machine	TRM-36 TRM-46 TRM-56		bits of wood, rice shell or peanuts shell, etc	The pressed density is adjustable, range from 0.8 to 1.4g/cm³. moisture content reaches to 30%.Forming can be done even the environment temperature is as low as-20°	US $2,000 - 3,000	China	http://www.alibaba.com/product-gs/225139523/Briquette_Press_biomass_briquette_machine.html
Briquette Press biomass briquette machine	TRM-36-66		Straw and husk rod or lump.	The pressed density is adjustable, range from 0.8 to 1.4g/cm³. moisture content reaches to 30%.Forming can be done even the environment temperature is as low as-20°	US $3,000 - 10,000	China	http://www.alibaba.com/product-gs/225139167/Briquette_Press_biomass_briquette_machine.html

GEM CO				Capacity: 400-600 kg/h energy consumption is less than 70 Kwh/h diameter of fuel briquette is 50 mm120mm.The density is about 1.3 .	the oil pressure in pipelines has reduced by 50% than other similar hydraulic machine .	EUR 18,300 - 19,400	China	http://www.alibaba.com/product-gs/205496832/Biomass_Briquetting_Hydraulic_Machine_Briquette_Press.html
HD	SKJ Series		sawdust, rice husk, cotton stalks, cottonseed skins, weeds and other crop	Capacity 100-400 kg/h Power(kw)11-320		US $888 - 888,888	China	http://www.alibaba.com/product-gs/347780199/Rice_Husk_Briquetting_Machine.html

Sanjin	IV		Wood Chips	Power: 15 kw Capacity: 140-200kg/h Dimension: 1.67*0.68*1.55 m material water content <=12%		China	http://www.alibaba.com/product-gs/257427646/coconut_shell_briquette_machine.html
Ming Yang	ZBJ-10			Capacity: 250-300kg/h power: 22kw size: 1.7x0.8x1.3 The size of raw materials: less than 5mm. Moisture:8-12%	US $1,900 - 4,800	China	http://www.alibaba.com/product-gs/323914002/BBQ_briquetting_machine_power_22kw.html

APPENDIX B1: Tillable Land Area in Land Capability Classes in Ontario Regions

Ontario Region	**Land Capability Classes**	**Percentage of land used for energy crop production**				
		5%	**10%**	**25%**	**60%**	**100%**
	1	11,905	23,810	59,526	142,861	238,102
Southern	2	43,833	87,666	219,166	525,998	876,664
	3	20,705	41,411	103,527	248,465	414,109
	4	1,857	3,714	9,285	22,283	37,138
	5	1,967	3,933	9,833	23,599	39,332
Western	1	36,242	72,483	181,208	434,899	724,831
	2	12,703	25,407	63,517	152,440	254,067
	3	11,957	23,913	59,783	143,478	239,130
	4	11,957	23,913	59,783	143,478	239,130
	5	6,505	13,009	32,523	78,055	130,091
Central	1	8,292	16,583	41,458	99,498	165,830
	2	5,676	11,353	28,382	68,116	113,526
	3	6,142	12,284	30,710	73,703	122,839
	4	5,949	11,898	29,744	71,386	118,976
	5	4,221	8,442	21,106	50,654	84,424
Eastern	1	1,600	3,201	8,001	19,203	32,005
	2	15,628	31,257	78,142	187,540	312,567
	3	15,242	30,484	76,210	182,905	304,841
	4	7,424	14,847	37,118	89,083	148,471
	5	3,258	6,517	16,292	39,100	65,166
Northern	1	539	1,078	2,694	6,465	10,775
	2	345	690	1,726	4,142	6,903
	3	900	1,800	4,501	10,801	18,002
	4	987	1,974	4,934	11,841	19,735
	5	563	1,126	2,816	6,757	11,262

APPENDIX B2: Estimates of potential biomass production on percentages of Land Capability Classes

	LAND CLASS	**Production (tDM/yr)**				
ONTARIO REGIONS		**Percentage of land used for energy crop production**				
		5%	**10%**	**25%**	**60%**	**100%**
Miscanthus	1	142,860	285,720	714,312	1,714,332	2,857,224
Southern	2	525,996	1,051,992	2,629,992	6,311,976	10,519,968
	3	227,755	455,521	1,138,797	2,733,115	4,555,199
	4	14,856	29,712	74,280	178,264	297,104
	5	13,769	27,531	68,831	165,193	275,324
	ALL	**925,236**	**1,850,476**	**4,626,212**	**11,102,880**	**18,504,819**
Western	1	434,904	869,796	2,174,496	5,218,788	8,697,972
	2	152,436	304,884	762,204	1,829,280	3,048,804
	3	131,527	263,043	657,613	1,578,258	2,630,430
	4	29,248	58,488	146,224	350,936	1,913,040
	5	45,535	91,063	227,661	546,385	910,637
	ALL	**793,650**	**1,587,274**	**3,968,198**	**9,523,647**	**17,200,883**
Central	1	99,504	198,996	497,496	1,193,976	1,989,960
	2	68,112	136,236	340,584	817,392	1,362,312
	3	67,562	135,124	337,810	810,733	1,351,229
	4	47,592	95,184	237,952	571,088	951,808
	5	29,547	59,094	147,742	354,578	590,968
	ALL	**312,317**	**624,634**	**1,561,584**	**3,747,767**	**6,246,277**
Eastern	1	19,200	38,412	96,012	230,436	384,060
	2	187,536	375,084	937,704	2,250,480	3,750,804
	3	167,662	335,324	838,310	2,011,955	3,353,251
	4	59,392	118,776	296,944	712,664	1,187,768
	5	22,806	45,619	114,044	273,700	456,162
	ALL	**456,596**	**913,215**	**2,283,014**	**5,479,235**	**9,132,045**
Northern	1	6,468	12,936	32,328	77,580	129,300
	2	4,140	8,280	20,712	49,704	82,836
	3	9,900	19,800	49,511	118,811	198,022
	4	7,896	15,792	39,472	94,728	157,880
	5	3,941	7,882	19,712	47,299	78,834
	ALL	**32,345**	**64,690**	**161,735**	**388,122**	**646,872**
Ontario Total		**2,520,144**	**5,040,289**	**12,600,743**	**30,241,651**	**51,730,896**
		5%	**10%**	**25%**	**60%**	**100%**
Switchgrass	1	83,335	166,670	416,682	1,000,027	1,666,714
Southern	2	306,831	613,662	1,534,162	3,681,986	6,136,648
	3	130,442	260,889	652,220	1,565,330	2,608,887

	4	10,399	20,798	51,996	124,785	207,973
	5	11,015	22,025	55,065	132,154	220,259
	ALL	**542,022**	**1,084,045**	**2,710,125**	**6,504,282**	**10,840,481**
Western	1	253,694	507,381	1,268,456	3,044,293	5,073,817
	2	88,921	177,849	444,619	1,067,080	1,778,469
	3	75,329	150,652	376,633	903,911	1,506,519
	4	20,474	40,942	102,357	245,655	1,339,128
	5	36,428	72,850	182,129	437,108	728,510
	ALL	**474,846**	**949,674**	**2,374,194**	**5,698,048**	**10,426,443**
Central	1	58,044	116,081	290,206	696,486	1,160,810
	2	39,732	79,471	198,674	476,812	794,682
	3	38,695	77,389	193,473	464,329	773,886
	4	33,314	66,629	166,566	399,762	666,266
	5	23,638	47,275	118,194	283,662	472,774
	ALL	**193,423**	**386,845**	**967,113**	**2,321,051**	**3,868,418**
Eastern	1	11,200	22,407	56,007	134,421	224,035
	2	109,396	218,799	546,994	1,312,780	2,187,969
	3	96,025	192,049	480,123	1,152,302	1,920,498
	4	41,574	83,143	207,861	498,865	831,438
	5	18,245	36,495	91,235	218,960	364,930
	ALL	**276,440**	**552,894**	**1,382,220**	**3,317,327**	**5,528,870**
Northern	1	3,773	7,546	18,858	45,255	75,425
	2	2,415	4,830	12,082	28,994	48,321
	3	5,670	11,340	28,356	68,046	113,413
	4	5,527	11,054	27,630	66,310	110,516
	5	3,153	6,306	15,770	37,839	63,067
	ALL	**20,538**	**41,076**	**102,696**	**246,444**	**410,742**
Ontario Total		**1,507,268**	**3,014,534**	**7,536,348**	**18,087,152**	**31,074,954**
Reed canarygrass (RCG)		**5%**	**10%**	**25%**	**60%**	**100%**
	1	113,098	226,195	565,497	1,357,180	2,261,969
Southern	2	416,414	832,827	2,082,077	4,996,981	8,328,308
	3	165,640	331,288	828,216	1,987,720	3,312,872
	4	12,999	25,998	64,995	155,981	259,966
	5	11,802	23,598	58,998	141,594	235,992
	ALL	**719,952**	**1,439,906**	**3,599,783**	**8,639,456**	**14,399,107**

Western	1	344,299	688,589	1,721,476	4,131,541	6,885,895
	2	120,679	241,367	603,412	1,448,180	2,413,637
	3	95,656	191,304	478,264	1,147,824	1,913,040
	4	25,592	51,177	127,946	307,069	1,673,910
	5	39,030	78,054	195,138	468,330	780,546
	ALL	**625,256**	**1,250,490**	**3,126,236**	**7,502,944**	**13,667,027**
Central	1	78,774	157,539	393,851	945,231	1,575,385
	2	53,922	107,854	269,629	647,102	1,078,497
	3	49,136	98,272	245,680	589,624	982,712
	4	41,643	83,286	208,208	499,702	832,832
	5	25,326	50,652	126,636	303,924	506,544
	ALL	**248,801**	**497,602**	**1,244,004**	**2,985,583**	**4,975,970**
Eastern	1	15,200	30,410	76,010	182,429	304,048
	2	148,466	296,942	742,349	1,781,630	2,969,387
	3	121,936	243,872	609,680	1,463,240	2,438,728
	4	51,968	103,929	259,826	623,581	1,039,297
	5	19,548	39,102	97,752	234,600	390,996
	ALL	**357,118**	**714,254**	**1,785,617**	**4,285,480**	**7,142,455**
Northern	1	5,121	10,241	25,593	61,418	102,363
	2	3,278	6,555	16,397	39,349	65,579
	3	7,200	14,400	36,008	86,408	144,016
	4	6,909	13,818	34,538	82,887	138,145
	5	3,378	6,756	16,896	40,542	67,572
	ALL	**25,885**	**51,770**	**129,432**	**310,604**	**517,674**
Ontario Total		**1,977,012**	**3,954,022**	**9,885,072**	**23,724,065**	**40,702,233**
High-Biomass Sorghum (HBS)		**5%**	**10%**	**25%**	**60%**	**100%**
Southern	1	130,955	261,910	654,786	1,571,471	2,619,122
	2	482,163	964,326	2,410,826	5,785,978	9,643,304
	3	207,050	414,110	1,035,270	2,484,650	4,141,090
	4	14,856	29,712	74,280	178,264	297,104
	5	13,769	27,531	68,831	165,193	275,324
	ALL	**848,793**	**1,697,589**	**4,243,993**	**10,185,556**	**16,975,944**
Western	1	398,662	797,313	1,993,288	4,783,889	7,973,141
	2	139,733	279,477	698,687	1,676,840	2,794,737
	3	119,570	239,130	597,830	1,434,780	2,391,300

	4	29,248	58,488	146,224	350,936	1,913,040
	5	45,535	91,063	227,661	546,385	910,637
	ALL	**732,748**	**1,465,471**	**3,663,690**	**8,792,830**	**15,982,855**
Central	1	91,212	182,413	456,038	1,094,478	1,824,130
	2	62,436	124,883	312,202	749,276	1,248,786
	3	61,420	122,840	307,100	737,030	1,228,390
	4	47,592	95,184	237,952	571,088	951,808
	5	29,547	59,094	147,742	354,578	590,968
	ALL	**292,207**	**584,414**	**1,461,034**	**3,506,450**	**5,844,082**
Eastern	1	17,600	35,211	88,011	211,233	352,055
	2	171,908	343,827	859,562	2,062,940	3,438,237
	3	152,420	304,840	762,100	1,829,050	3,048,410
	4	59,392	118,776	296,944	712,664	1,187,768
	5	22,806	45,619	114,044	273,700	456,162
	ALL	**424,126**	**848,273**	**2,120,661**	**5,089,587**	**8,482,632**
Northern	1	5,929	11,858	29,634	71,115	118,525
	2	3,795	7,590	18,986	45,562	75,933
	3	9,000	18,000	45,010	108,010	180,020
	4	7,896	15,792	39,472	94,728	157,880
	5	3,941	7,882	19,712	47,299	78,834
	ALL	**30,561**	**61,122**	**152,814**	**366,714**	**611,192**
Ontario Total		**2,328,435**	**4,656,869**	**11,642,192**	**27,941,137**	**47,896,705**
Hybrid Poplar		**5%**	**10%**	**25%**	**60%**	**100%**
Southern	1	190,480	380,960	952,416	2,285,776	3,809,632
	2	701,328	1,402,656	3,506,656	8,415,968	14,026,624
	3	186,345	372,699	931,743	2,236,185	3,726,981
	4	16,713	33,426	83,565	200,547	334,242
	5	13,769	27,531	68,831	165,193	275,324
	ALL	**1,108,635**	**2,217,272**	**5,543,211**	**13,303,669**	**22,172,803**
Western	1	579,872	1,159,728	2,899,328	6,958,384	11,597,296
	2	203,248	406,512	1,016,272	2,439,040	4,065,072
	3	107,613	215,217	538,047	1,291,302	2,152,170
	4	32,904	65,799	164,502	394,803	2,152,170
	5	45,535	91,063	227,661	546,385	910,637
	ALL	**969,172**	**1,938,319**	**4,845,810**	**11,629,914**	**20,877,345**

Central	1	132,672	265,328	663,328	1,591,968	2,653,280
	2	90,816	181,648	454,112	1,089,856	1,816,416
	3	55,278	110,556	276,390	663,327	1,105,551
	4	53,541	107,082	267,696	642,474	1,070,784
	5	29,547	59,094	147,742	354,578	590,968
	ALL	**361,854**	**723,708**	**1,809,268**	**4,342,203**	**7,236,999**
Eastern	1	25,600	51,216	128,016	307,248	512,080
	2	250,048	500,112	1,250,272	3,000,640	5,001,072
	3	137,178	274,356	685,890	1,646,145	2,743,569
	4	66,816	133,623	334,062	801,747	1,336,239
	5	22,806	45,619	114,044	273,700	456,162
	ALL	**502,448**	**1,004,926**	**2,512,284**	**6,029,480**	**10,049,122**
Northern	1	8,624	17,248	43,104	103,440	172,400
	2	5,520	11,040	27,616	66,272	110,448
	3	8,100	16,200	40,509	97,209	162,018
	4	8,883	17,766	44,406	106,569	177,615
	5	3,941	7,882	19,712	47,299	78,834
	ALL	**35,068**	**70,136**	**175,347**	**420,789**	**701,315**
Ontario Total		**2,977,177**	**5,954,361**	**14,885,920**	**35,726,055**	**61,037,584**