Life Cycle Assessment of Switchgrass (*Panicum virgatum* L.) Biomass Production in Ontario

by

Binu Kalita

A Thesis
presented to
The University of Guelph

In partial fulfilment of requirements
for the degree of
Master of Science
in
Plant Agriculture

Guelph, Ontario, Canada

ABSTRACT

LIFE CYCLE ASSESSMENT OF SWITCHGRASS (*Panicum virgatum* L.) BIOMASS PRODUCTION IN ONTARIO

Binu Kalita
University of Guelph, 2012

Advisor:
Professor Amar Mohanty

Abstract: Commercial cultivation of switchgrass in Ontario is limited mainly due to inadequate market opportunities. However, recent developments in bioproducts identify switchgrass as a promising biomass crop for bioenergy and biomaterials applications. At present, assessment of environmental impact of growing switchgrass in Ontario is lacking. Therefore, this study was conducted to evaluate the energy use and environmental impacts of switchgrass biomass production in Ontario through life cycle assessment. Cradle-to-farm gate life cycle assessment was conducted following the ISO 14040/14044 guidelines. Life cycle inventory data were collected from farmers, experts and available literature. Life cycle impact assessment was conducted for energy use and environmental impacts using the SimaPro software. Life cycle processes related to fertilization, harvesting and soil N emission were identified as major hot spots for energy and environmental impacts. Improving efficiency of energy, inputs and biomass yield will reduce the environmental burden associated with growing switchgrass in Ontario.

ACKNOWLEDGEMENTS

I would like to offer my sincere gratitude to my supervisor, Professor Amar Mohanty, who has supported me throughout my research work. My sincere thanks are due to the advisory committee members, Dr. Goretty Dias, Dr. Manju Misra, Dr. Bill Deen and Dr. Claudia Wagner-Riddle for their advice and support during the course of this study. The technical guidance in LCA and encouragements received from Dr. Goretty Dias were instrumental towards this accomplishment.

A few switchgrass farmers of Ontario must be credited for their help and cooperation by providing information on their cultivation practices. Special mention must be made of Mr. Don Nott for his time and excellent support by providing data through interview and emails despite his busy schedule. Expert comments and information on switchgrass cultivation provided by Scott Banks from the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) are duly acknowledged.

The role of the Ontario Ministry of Agriculture, Food and Rural Affairs was crucial in successful completion of my research and the Master’s degree through research funding, Highly Qualified Personnel Scholarship and job shadowing opportunity.

I thank my cheerful group of fellow students for their encouragement and sharing helpful ideas and thus making a memorable experience in my life.

I am indebted to my sons Rubin and Ayan, and my husband who every day encouraged me through their smile. Finally, I thank all others who directly or indirectly supported me in this endeavour.

TABLE OF CONTENTS

Chapter 1: INTRODUCTION

Chapter 2: LITERATURE REVIEW

Chapter 3: MATERIALS AND METHODS

Chapter 4: RESULTS

Chapter 5: DISCUSSION

APPENDIX

LIST OF TABLES

(Please note that Tables 4.3, 4.4, 4.5, 4.6, 4.7, 4.8 and 4.9 are listed in Appendix)

LIST OF FIGURES

List of Abbreviations

ai: Active ingredient

2, 4-D: 2, 4-Dichlorophenoxy acetic acid

Btu: British thermal unit

CFC: Chlorofluorocarbon

C_3: Plants that produce 3-phosphoglycerate (3 carbon compound) as the first stable product of photosynthetic CO_2 fixation

C_4: Plants that produce oxaloacetate (4 carbon compound) as the first stable product of photosynthetic CO_2 fixation

CO_2 eq: Carbon dioxide equivalent

CO_2 e-C: Carbon dioxide equivalent of carbon

CO2 e-C.$m^{-2}yr^{-1}$: Carbon dioxide equivalent of carbon per meter square per year

CO_2: Carbon dioxide

CO: Carbon monoxide

E85: An ethanol fuel blend of up to 85% denatured ethanol fuel and gasoline by volume

EPA: United States Environmental Protection Agency

F1: Filial 1(First generation offspring from crossing between two parents)

g: Gram

GHG: Greenhouse gases

GJ: Gigajoule

GWP: Global warming potential

ha: Hectare

HP: Horse power

HS1 and HS2: Harvest system1 and Harvest system 2

IPCC: Intergovernmental Panel on Climate Change

ISO: International Organization of Standardization

kg: Kilogram

km: kilometer

kt: kilotons

L: Litre

LCA: Life cycle assessment (or analysis)

LCI: Life cycle inventory

LCIA: Life cycle impact assessment

LC_{50}**: (**Lethal Concentration 50): concentration that kills 50% of a sample population.

MJ: mega joule

N: Nitrogen

NH_3: Ammonia

N_2O: Nitrous oxide

NO_x: Nitrogen oxides

OSR: Oil Seed Rape

P: Phosphorus

PM: Particulate matter

REAP: Resource Efficient Agricultural Production

SOC: Soil organic carbon

SO_2: Sulfur dioxide

t: tonne

TRACI: Tool for the Reduction and Assessment of Chemical and other environmental Impacts

CHAPTER 1

INTRODUCTION

1.1 Impacts of fossil fuel use

Fossil fuels have contributed significantly to the growth of the world economy and standard of living in industrialized society. Eighty five percent of the total primary energy used globally came from fossil fuels in 2008 (IPCC 2011). However, this use has come at a cost to the environment and long term sustainability. There is a rising awareness and understanding of the environmental changes in the world over the last few decades. Increase in carbon dioxide (CO_2) concentration in the atmosphere due to combustion of fossil fuels and deforestation have been the largest man-made impacts on the global carbon cycle (Janzen, 2004). It was estimated that the fossil fuels used by humans in 1997 were generated from ancient organic matters that contained approximately 44×10^{18} grams of carbon and production of this carbon required energy more than 400 times the earth's current net primary productivity (Dukes, 2003). Carbon dioxide emissions grew by about 80% between 1970 and 2004, primarily due to increased use of fossil fuel and are predicted to rise even more rapidly in the coming decades (Intergovernmental Panel on Climate Change, 2007). Over the last 20 years, global CO_2 emission has grown from 22.7 billion tonnes in 1990 to 33 billion tonnes in 2010, registering an increase of 45% (Olivier et al., 2011). Moreover, fossil fuel combustion contributed 56.6% of the all anthropogenic greenhouse gas emissions (Rogner et al., 2007). Besides air quality concerns in cities due to presence of nitrogen oxides, smog and air-borne particulates are also attributed to the use of fossil fuels. Thus, there are undeniable signs that climate change is a serious threat facing the planet (Ragauskas et al., 2006). Managing these environmental changes is becoming a major challenge for humankind and is essential for protecting the environment and preserving ecological systems.

The global energy supply and security are at risk due to rise in global demand, depletion of fossil resources and fluctuating prices. Global oil markets are in a period of increased scarcity, reflecting rapid growth in oil demand in emerging economies and a downshift in oil supply growth. The environmental burdens and energy security associated with fossil energy sources are the two key causes that have triggered interest in exploring for renewable resources as alternative to fossil based resources for various markets. Abundant biobased sources (Wood and Layzell, 2003), its renewability, potential for increasing production (and productivity) make biomass a promising alternative in replacing fossil based products. Biomass from agriculture and forestry are being used in various materials, chemicals, fuels and energy products to replace fossil fuels (Natural Resources Canada, 2008).

1.2 Importance of bioproducts industry

Biobased products have been an integral part in the progress of human civilization since ancient times. The predominance of petroleum resources over the last century increased our dependence on fossil-based products for diverse applications like energy, chemicals and industrial materials. However, a new transformation is under way around the globe favouring use of products and processes that are sustainable, renewable and green. This results in a fundamental change from utilizing fossil carbon to renewable carbon or biomass as a feedstock for energy and manufacturing industries. Countries around the world are identifying biomass as a potential source of renewable and sustainable energy, chemicals and materials; in essence, biomass will provide the feedstock for a bio-based economy. Globally, the annual production of biomass from plant vegetation is equal to five times the world's annual consumption of energy and chemicals (Industry Canada, 2010).

Canada has a large, vegetated land mass and well-developed forest and agricultural industries (Wood and Layzell, 2003). Consequently, this nation is likely to have a 'green advantage' for the use of biomass as a source of renewable energy, chemicals and materials. A recent report (Sparling et al., 2010) suggested that over 81% of Canada's bioproduct industry in 2009 was composed of small firms, and agricultural biomass was used as the primary source of feedstock by 44% of the bioproducts firms. Biomass, and in particular dedicated biomass crops, has attracted attention as a promising means to develop local, sustainable energy sources and other biobased products. It has been recognized that Canada's abundant biological resources with technology-based opportunities could be utilized to grow the economy and protect the environment and our quality of life (Industry Canada, 2010).

1.3 Switchgrass as a feedstock for bio-based industry

Switchgrass (*Panicum virgatum* L) is a non-food perennial warm season grass native to North America and is considered as one of the most valuable sources of biomass (Samson, 2007; Rinehart, 2006). This crop was identified as a model herbaceous energy crop by the US Department of Energy (McLaughlin, 1993). Switchgrass shows promise due to a number of features including moderate to high productivity, adaptation to marginal farmlands, drought resistance, stand longevity, low fertilizer requirements, resistance to pests and diseases, environmental benefits and flexibility for different value-added uses (McLaughlin et al., 1999; Samson et al., 1993). In Canada, researchers were attracted to study the potential use of switchgrass for biomass production due to its excellent growth performance (Girouard et al., 1999; Madakadze et al., 1998). Resource Efficient Agricultural Production (REAP) Canada has done extensive research on switchgrass and its sustainability for bioheat and bioethanol production in Canada revealing that switchgrass has significant potential to use as a feedstock for bio-industry applications (Samson, 2009).

Being a C_4 crop, switchgrass is forty percent more efficient in photosynthetic activity than C_3 crops and thus the energy output potential is higher (Samson et al., 2005). The higher photosynthetic efficiency resulted in a net energy gain per hectare (approximately sixty percent higher than grain corn). Besides, the high cellulosic content of switchgrass makes it an ideal candidate for ethanol production and combustion fuel source for power production (Rinehart, 2006).

Although switchgrass has been studied globally for its potential as a feedstock for bio-energy, bio-fuel and biomaterials, its utilization in a wide variety of bioproducts is still an emerging market, mostly in research and demonstration phase. Energy crops, such as switchgrass, miscanthus (*Miscanthus spps*) and other prairie grasses, are perennial in nature and thus require less intensive management practices than conventional food crops. Overall, the fertilizer and agrochemical input requirement are less for energy crops than conventional agricultural crops (McLaughlin and Kszos, 2005; Mitchell et al, 2008). There are a number of studies available on the agronomical aspects of energy crops (Adler et al., 2007; Lewandowski et al., 2003; Qin et al., 2006; Venturi and Venturi, 2003); however, the environmental impacts of energy crop cultivation are still debated and a better understanding of the environmental impacts associated with energy crop is necessary for sustainable cultivation of these crops (Monti et al., 2009).

1.4 Environmental sustainability study for the biomass crops

Agricultural crop production systems are heavily dependent on fossil fuels for synthetic fertilizer production, pesticide/ herbicide production, and application and supplying fuel for farm machinery and irrigation (Pimentel et al., 2005). This energy intensive agriculture has been associated with a broad range of ecological impacts, including water pollution (Carpenter et al., 1998), soil erosion (Gerhardt, 1997), pesticide toxicity and selection for pest resistance (Carvalho, 2006). Moreover, the finite nature of fossil fuel reserves as well as the macro scale environmental impacts of extracting and consuming the fossil energy that underpins intensive agriculture are of increasing concern (Pimentel et al., 2005) and merit closer attention.

The environmental impact of biomass cropping systems is an important consideration for various potential uses of biomass in industrial processes and related policy development. Earlier studies in Europe and the USA have shown that perennial rhizomatous grasses are more promising and sustainable source of biomass due to higher yield potential and low input demands (Lewandowski et al., 2003). Biomass crops for energy use are considered a less intensive form of agriculture than food cropping (Jannasch et al., 2001a) as most of these crops like switchgrass, miscanthus and other prairie grasses are perennial in nature and thus require less intensive management practices including various inputs. These crops also have the potential to be more efficient in their use of fertilizers due to nutrient retention and cycling between the growing years. Thus the benefit of growing biomass crops ranges from positive effects on soil quality and stability, its cover value for wildlife, to relatively low inputs of energy, water and agrochemicals required per unit of energy produced (Keshwani and Cheng, 2009). The calculated carbon sequestration rates of switchgrass are 20-30 times higher than that of annual crops such as corn *(Zea mays)* (McLaughlin and Walsh, 1998). These differences have major implications for both the rate and efficiency with which fossil energy sources can be replaced with cleaner burning biofuels.

A comparison of the energy budgets for corn ethanol and switchgrass ethanol reveals that the efficiency of energy production from switchgrass is fifteen times more than corn (McLaughlin and Walsh, 1998). The lower energy requirements to produce and convert switchgrass to ethanol result in a twenty times reduction of the CO_2 emissions per unit of land area with switchgrass compared to corn. Thus potential reductions in CO_2 emissions, tied to the energetic efficiency of producing transportation fuels and replacing non-renewable petrochemical fuels with ethanol derived from switchgrass are very promising. Research on herbaceous energy crops primarily focuses on quantification of changes in soil nutrient and soil organic matter to know the long-term changes in soil quality through annual biomass removal (McLaughlin and Walsh, 1998). But, there are still only a limited number of studies available on comprehensive life cycle assessment of perennial energy crops to determine qualitative and quantitative environmental impacts of the cultivation practices (Monti et al., 2009). Earlier studies also reported that agricultural production processes accounted for 27% to 44% of the total energy consumption in producing biobased product (Shapouri et al. 1995; Wang et al. 1999).

In Ontario, switchgrass pellets are mainly used for greenhouse and residential heating (Samson et al., 2000). Earlier studies on switchgrass in Ontario helped to develop a management guide for switchgrass production (Samson, 2007). Due to increasing interest in potential uses of switchgrass for energy and materials applications in Ontario, a detailed study on environmental impact of switchgrass cultivation is required. There is no published data available for Ontario on switchgrass life cycle inventory (inputs required for production of switchgrass) and life cycle impact assessment (global warming potential, acidification, eutrophication etc.) focusing on various agricultural practices. Therefore the present study was undertaken to fill this knowledge gap.

1.5 Goal of the study

It is evident that switchgrass has potential as a biomass crop for different bio-based industries and its utilization is an emerging market. The Bioproducts Discovery and Development Center at the University of Guelph is working with farmers and other industrial partners on the development of switchgrass based biocomposites for different applications. This research has shown the potential of using switchgrass as reinforcing filler with bioplastic and with the traditional plastic matrices to develop biocomposite where switchgrass replaces the glass fibre to a considerable extent. This application of switchgrass provides a value added use for the industrial products. There is also growing interest among Ontario farmers to grow this crop as a source of biomass for various potential applications including bioenergy such as Ontario Power Generation's initiative to replace coal (OMAFRA, 2010). This has driven the need to know more about the environmental impacts of growing switchgrass as a feedstock for different value added applications. This knowledge would be helpful for commercialization of switchgrass based bioproducts. Currently, there is no published research related to the environmental impacts of cultivation practices of switchgrass in Ontario. Therefore, a better understanding of the biomass production system and its environmental performance was identified as a major knowledge gap. This study was conducted to quantify the total energy use and emissions that are associated with switchgrass cultivation and management from cradle to farm gate using the ISO 14040-14044, 2006 LCA standards. Identification of energy and emission hot spots in switchgrass cultivation will be useful to farmers and researchers to:

- know which aspects of the switchgrass life cycle can be improved through changes in field practices or varietal improvement that reduce the environmental impacts and
- support policy and program development and regulation on energy crops for different value-added applications.

The present study is an internal LCA of swichgrass for the Bioproducts Discovery and Development Center, University of Guelph. As the Centre is developing various switchgrass-based biomaterials, the internal LCA will contribute towards better understanding of the environmental performance of these biomaterials in replacing fossil based components.

The objectives of this research were:

- To acquire and compile farm data on agronomic practices and inputs used in growing switchgrass in Ontario.
- To study the environmental impacts of growing switchgrass in Ontario farms in terms of total energy use and emissions (global warming potential, acidification, eutrophication, toxicity, smog and ozone depletion).
- To identify the hot spots of energy use and emissions in switchgrass cultivation practices and thus to identify and target agronomic practices for improving efficiency and environmental performance of biomass production.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction to Switchgrass

2.1.1. History and ecotypes

Switchgrass (*Panicum virgatum* L.) is a perennial warm-season C_4 grass native to North America (Keshwani and Cheng, 2009), that occurs naturally in the east of the Rocky Mountains and south of 55°N latitude down into Mexico and Central America (Moser and Vogel, 1995). This grass has been used for soil conservation and as a forage crop in North America, as fodder crop in South America and Africa, and as ornamental crop in Europe and America (Elbersen et al., 2001). Among the 1745 known species of C_4 warm season grasses in the world, switchgrass is identified as suitable crop for growing in temperate climates i.e. the climate of middle latitude (Stander, 1989). Research on switchgrass started in the USA in 1940s as a summer forage crop (Samson, 2007). Since then, switchgrass has been identified as a promising bioenergy (biofuel) feedstock through studies conducted by the U.S. Department of Energy (Samson, 2007). The excellent growth performance of switchgrass attracted the Canadian researchers to analyse the potential use of this crop for biomass in Canada (Girouard et al., 1996; Madakadze et al., 1998). In 1991, Resource Efficient Agricultural Production (REAP) Canada was the first agency in Canada to begin a research program on warm season perennial grasses for renewable energy applications including bioheat and bioethanol (Samson, 2009). The experimental plots of switchgrass as a biomass crop have been established in the provinces of Quebec and Ontario since 1993 (Girouard et al., 1996). The field studies conducted in south-western Quebec revealed that out of 22 warm season species, switchgrass and cord grass performed best in terms of their growth performance and biomass production (Madakadze et al., 1998).

Across North America, switchgrass has grown naturally and natural variation within the species presents substantial morphological diversity and a wide range of adaptation (Parrish and Fike, 2005). Because switchgrass has evolved in many different environments like cold northern and warm southern areas, upland sites with shallow soils and in creek and river bottoms with deep soils, it has many ecotypes (Porter, 1966). Each ecotype is slightly different from others, but all belong to the same species. Based on morphological characteristics and habitat preferences, swichgrass is classified into two ecotypes-lowland and upland. The lowland types are tall, coarse, rapid growing, bunch type growth habit and are found in floodplains. The upland types are shorter than lowland types, fine stemmed, and are found in drier upland sites and are often semi-decumbent (Moser and Vogel, 1995; Porter, 1966). The upland ecotypes usually grow 1.5 to 1.8 m tall and are adapted to relatively shallow soils. Lowland types, which grow up to 3.7m tall, are typically found on deep soils. Lowland ecotypes are not winter hardy in eastern Canada (Jannasch et al., 2001). Lowland and upland tetraploids have been crossed to produce true F_1 hybrids that showed 30-50% yield increase (Vogel and Mitchell, 2008).

Switchgrass is a cross-pollinated species and has two common ploidy levels (number of chromosome sets). Most varieties are tetraploids or octaploids. Generally, upland types are either octaploid or tetraploids, whereas lowland types are tetraploid (Vogel, 2004). The basic chromosome number of switchgrass is x = 9. The ploidy levels of switchgrass range from diploid (2n=18) to dodecaploid (2n=12x=108) (Hultquist et al., 1996; McMillan, 1959; Nielsen, 1944; Riley and Vogel, 1982).

Under Canadian conditions, several switchgrass varieties were tested for yield and days to maturity. The yield level was found to vary in the range of about 6 – 13 t ha^{-1} depending on the variety (Jannasch et al., 2001). In general, higher yielding varieties (above 10 t ha^{-1}) took longer time (about 135 days) to mature. The Cave-In-Rock variety with an average annual yield of 11.6 ton dry matter ha^{-1} (135 days maturity) in Quebec, Canada conditions is widely recommended for North American climatic and soil condition (Jannasch et al., 2001). Eight to ten kg ha^{-1} pure live seed is recommended for successful establishment (Samson, 2007) of switchgrass.

2.1.2. Advantages of switchgrass as a biomass crop

A sustainable biomass must be productive, protective of soil and water resources and should be profitable to the producers. Switchgrass meets all these requirements to be a potential biomass crop. Switchgrass is a non-food perennial grass and shows promise as a biomass crop due to its high productivity, suitability for marginal land, low water and nutritional requirements and flexibility for different value-added uses (McLaughlin, 1999; McLaughlin and Walsh, 1998). The productivity of switchgrass in Canadian climate is higher (10-12 t ha^{-1}) than several other major annual crops (grain corn: 6.5 t ha^{-1}; soybean: 2.17 t ha^{-1}). Some research finding suggested that switchgrass can produce biomass up to 26-34 t ha^{-1} yr^{-1} in various locations in the U.S. depending on the harvest frequency (number of cut per year) and time, and the rate of nitrogen fertilizer applied (Sanderson, 1996; Thomason, 2004). Suitable cultivars have been identified throughout much of the U.S. agricultural land base, with yields of 10-16 t ha^{-1} in central and 15-23 t ha^{-1} in southern U.S. (Samson et al., 2005). For the southern Canadian prairies the modest yield is 4.3-7.0 t ha^{-1} (Jefferson et al., 2002) while for eastern Canada, yield is 10-12 t ha^{-1} (Samson et al., 1997). Switchgrass has high yield potential and can adapt to marginal cropland, and remain productive in most rain-fed production systems for ten to fifteen years (Vogel, 2004). Dunn et al. (1993) identified environmental benefits associated with the perennial nature of switchgrass such as less intensive agricultural management practices, reduced energy and agrochemical consumption and positive effects on soil and wildlife quality. Due to its perennial nature and productive period of at least 10 years, switchgrass requires soil tillage only in the establishment year and thus reduces the risk of soil erosion (Ma et al., 1999). Compared to annual row crops like corn and soybean (*Glycine max* L), growing swichgrass reduces soil erosion (1% of erosion that caused by growing either corn and soybean) and also reduce the pesticide use to a great extent (Hohenstein and Wright, 1994). The deep root system of switchgrass can account for up to 80% of the total biomass (Liebig et al., 2005); increase in the water use efficiency by 50% (over cool season grasses) and contribute to rise in soil carbon storage (Stout et al., 1988). On an average, switchgrass stores 2899 kg of soil organic carbon ha^{-1} annually to a depth of 1.22 meter (Liebig et al., 2008). Moreover stress tolerance (drought and flooding tolerance, less prone to weed invasion, disease and pest resistance), hardiness in poor soil and climate conditions, widespread adaptability in temperate climates and relatively low input (fertilizer and herbicide) requirement are other agronomic advantages of switchgrass (Jannasch et al., 2001; Samson, 2008). The self-seeding property of switchgrass makes it more conducive to long term stand maintenance. Switchgrass can also be planted and harvested using conventional farm equipment and therefore poses no additional burden to the grower wishing to integrate this crop in the existing system (Lewandowski et al., 2003; Vogel and Jung, 2000). Lignocellulosic biomass feedstock had on an average 61% and 44% lower delivered cost as compared to oilseed (canola, soybean) and grain (corn) feedstock, respectively (Samson et al., 2008).

2.1.3. Switchgrass markets

Traditional uses of switchgrass include livestock bedding, straw bale housing, forage and dry cow ration, mulching and mushroom compost substrate. However, various new value added opportunities for switchgrass are increasingly being recognized (Samson, 2007).

Over the last decade, switchgrass has been developed for energy and fibre application in North America (Van den oever et al., 2003) and is an attractive biomass for use in pulp mills in eastern Ontario and Western Quebec, Canada (Fox et al., 1999).

Several studies established switchgrass as a promising feedstock for bioenergy in terms of direct combustion for heat and electricity generation, gasification, pyrolysis and cellulosic ethanol production (Bai et al., 2010; Cherubini and Jungmeier, 2009; Lewandowski et al., 2003; McLaughlin et al., 2002; Monti et al., 2009;). One of the bioenergy applications is pelletized fuel for commercial heating such as in greenhouses, livestock buildings, corn drying and biogas production (Samson, 2007). Biomass co-firing with coal is another way of utilizing renewable technology. Co-firing entails combusting a combination of biomass and coal in an existing coal-fired unit. Switchgrass co-firing with coal was found to be more favourable than switchgrass alone (Qin et al., 2006). The Bioenergy Feedstock Development Programme of the U.S. Department of Energy (DOE) has identified switchgrass as model species for biomass energy. Decentralized home heating system using switchgrass pellet is well developed in Canada. Cellulose ethanol technology using non-food biomass has been developed by Iogen Corporation and also by Greenfield Ethanol in Canada, however currently in demonstration phase. Feedstock price for switchgrass is reasonable ($100-$120 /t) however high cost of bioconversion is major bottleneck of cellulose ethanol technology to be commercialized at present. The complex structures of cellulose, hemicellulose, and lignin in lignocellulosic biomass makes the feedstock highly recalcitrant to bioconversion of its carbohydrates into ethanol compared with starch (Abramson et al., 2010; Somerville et al., 2010). Research is under way using transgenic approaches to modify the lignin pathways to make the bioconversion process easier that might lead to better economics for cellulose ethanol commercialization (Abramson et al., 2010).

Natural fibre composites (biocomposites) have been considered as emerging and viable alternative to glass fibre reinforced composites especially in automotive and building products applications (Mohanty et al., 2002), furniture (Hautala et al., 2004) and packaging industries (Bhattacharyya and Jayaraman, 2003). Plant based fibres (including switchgrass) are attractive reinforcing agents as compared to synthetic glass fiber in the manufacture of biocomposites due to several desirable properties like biodegradability, low density, high toughness, low cost and renewability. Switchgrass stems up to a length of 10 cm have been used as reinforcement to make lightweight composites with polypropylene (Zou et al., 2010). The study by Van den oever et al.(2003) showed that addition of 30% (by weight) switchgrass pulp as a reinforcing and filling agent (due to good quality & low cost fibre) in polypropylene based composites resulted in increase of flexural modulus by a factor of about 2.5 compared to pure polypropylene. Several research studies are in progress with commercialization potential of switchgrass in biomaterial applications at the University of Guelph, Canada. The Bioproducts Discovery and Development Centre of the University of Guelph has been using switchgrass and Miscanthus, crop residues and by-products as feedstock for various biomaterials application including automotive, building and other consumer goods. This centre is working with Ontario farmers and other academic and industrial partners to commercialize switchgrass in high value added biomaterials application. Recently, BDDC has fabricated natural fibre-based (including switchgrass) biocomposite bins that are being commercialized in partnership with industry and farmers (Vowles, 2011).

2.2 Environmental benefits of switchgrass:

The capacity of the perennial grasses to effect positive changes in soil properties is well documented (Follett et al., 2001). Switchgrass, being a perennial crop, has several environmental benefits, which include soil health improvement by carbon sequestration, soil erosion reduction by improving soil quality and stability, cover value for wildlife and relatively require low inputs (McLaughlin and Walsh,1998). This grass species can also provide habitat and food for many species of wildlife, including cover for large and small mammals, and a nesting place for wild turkey and quail.

2.2.1. Carbon sequestration

Carbon sequestration is a process of removal of CO_2 from the atmosphere for long term storage. The CO_2 stored by plants are transferred into the soil through crop residues, roots and other organic solids. This process helps off-set emissions from fossil fuel combustion and other carbon emitting activities while enhancing soil quality and improving crop productivity. The sequestration of carbon by crops is considered to be a very important strategy for reducing the atmospheric carbon (Lemus and Lal, 2005). Switchgrass stores a large portion of total mass belowground after the above ground biomass is harvested. In North America, carbon sequestration by switchgrass is extended across a broad range of growing conditions at a rate of 1.7-10.1 t ha^{-1} yr^{-1} which is equivalent to 6.2-37.0 t CO_2 ha^{-1} yr^{-1} (Frank et al., 2004; Lee et al., 2007). It has been reported that about 80% of total switchgrass biomass remains in soil (Frank et al., 2004). A comparative study of switchgrass and cropland sites, where paired sample were analysed in the U.S Great Plains, revealed that switchgrass planting increases soil organic carbon (SOC) by 15.3 t ha^{-1} (Liebig et al., 2005). This large increase in SOC is assumed to be due to a number of factors including root turnover of carbon by switchgrass roots and phytolith production (Samson et al., 2005). Switchgrass soil carbon sequestration rate is found to be 20-30 times higher than annual crops (McLaughlin and Walsh, 1998). Carbon sequestration can range from 1.1 to 2.9 t ha^{-1} at root depths 0-30 cm and 0-120 cm, respectively (Liebig et al., 2008) in central and northern Great Plains of the USA. The Chariton Valley study on switchgrass fields has revealed that fields with 3 - 14 year switchgrass stands add soil organic carbon (SOC) at a rate of 3.7 t $ha^{-1}yr^{-1}$ (Ney and Schnoor, 2002). Another study of carbon sequestration in southern Quebec, Canada showed that, at 0-15 cm soil depth willow and switchgrass plots had higher soil organic carbon than corn (35 t ha^{-1} for willow, 33 t ha^{-1} for switchgrass and 27 t ha^{-1} for corn) (Mehdi et al., 1998). Compared to most other crops, especially annuals, switchgrass shows the highest potential to store carbon in the root zone below the upper soil horizons (Mitchell et al., 2008). This suggests that site specific parameter like carbon sequestration by switchgrass crops can potentially offset the total greenhouse gas emission, resulting in reduction of total emissions on a life cycle basis.

2.2.2. Agricultural input

Switchgrass is less input intensive and inputs are largely limited to field operations necessary for establishment and harvesting of the crop. Switchgrass can be grown on soil of moderate fertility without fertilizing or with limited addition of fertilizer (Parrish and Fike, 2005). Compared to cool seasoned grasses, the warm season grasses like switchgrass rely on its fine root system to uptake phosphorus from soil (Hetrick et al., 1991). In North America, it was reported that tall grass prairie species like switchgrass is productive under low phosphorus (P) soil environment and its root system are highly dependent on mycorrhiza for P uptake (Samson et al., 2005). Additionally, the large root system of switchgrass makes it an excellent potassium scavenger and thus do not respond to potassium fertilizer. In Canada, no potassium or phosphorous fertilizer is applied in general for switchgrass cultivation (Samson, 2007). However soil concentrations of these two nutrients should be monitored every 2-3 years after establishment of this crop.

All nutrient inputs applied in crop cultivations are associated with some fossil fuel inputs with the exception of biological nitrogen fixation. The energy cost of manufacturing inorganic fertilizers and plant protection products is very high and also contribute to emission. Switchgrass generally requires less plant protection measures than the annual crops and thus has positive environmental effects by reducing greenhouse gas emissions.

2.2.3. Net energy balance

Net energy balance of crop production reflects the economic and environmental efficiency of the products derived from the crop. Figure 2.1 (based on data compiled by Samson et al., 2005) represents total fossil energy consumed (input), solar energy collected (energy in biomass i.e. output) and net energy balance (energy content of switchgrass minus fossil energy used) by one hectare of switchgrass crop. The input to output ratio (i.e. the ratio of the fossil energy required to grow the crop to that of energy produced by using the crop) is 1:22 for switchgrass which is significantly higher than several other crops like grain corn (1:5), canola (1:3), soybean (1:7), rye (1:3), tam hay (1:17) and oat (1:3).

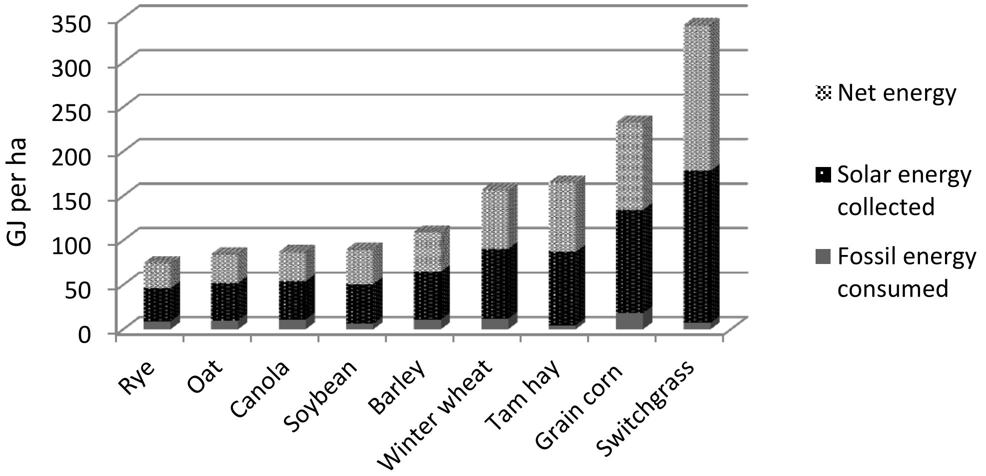

Figure 2.1: Solar energy collection (output) and fossil fuel energy consumed (input) of Ontario crops, Giga Joules (GJ) per hectare (Redrawn after the reference Samson et al., 2005)

Oilseeds such as canola and soybean are amongst the least efficient energy production systems (Figure 2.1). Grain corn is more efficient at biomass production than oilseed crops, but also has significantly higher energy requirements for its production cycle (Samson et al., 2005). Perennial warm-season grass like switchgrass is a more efficient collector of solar radiation and has lower energy input requirements in its production cycle (because of its perennial C_4 nature and low nitrogen requirements).

2.2.4. Energy and greenhouse gas (GHG) offset potential

Switchgrass has been identified as less energy intensive biomass crop and also has the potential to reduce GHG emission through its biomass production and application in biobased industry as well. Resource Efficient Agricultural Production (REAP) Canada reported that a considerable emission reduction is possible from combustion of switchgrass pellets compare to the fossil resources. Use of switchgrass pellets as an alternative for home heating can offset 86% GHG emission if replace natural gas, 91% GHG reduction by replacing coal and equal to 91% reduction if replaces heating oil (Samson et al., 2008).

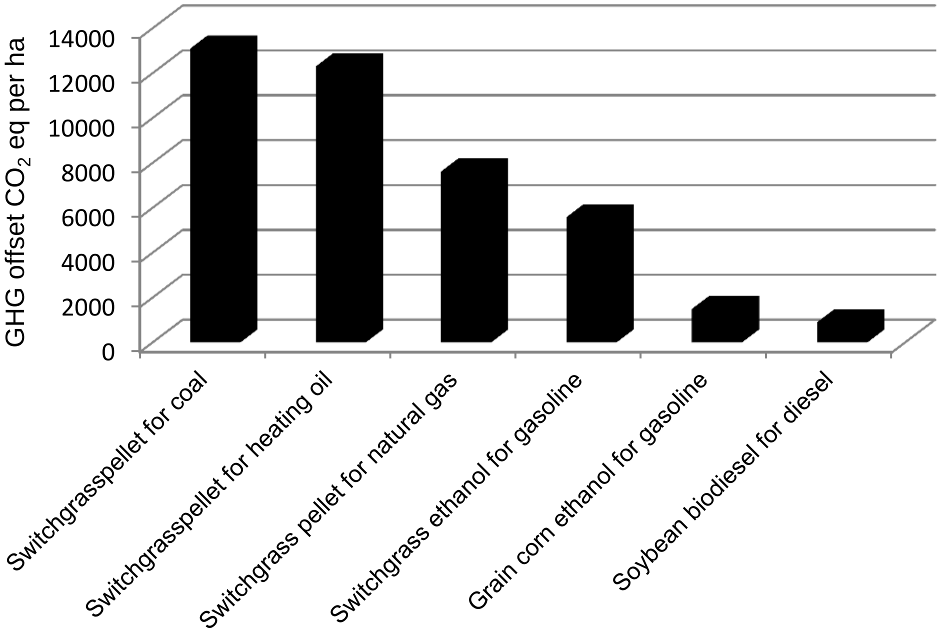

Figure 2.2: GHG emission offset potential of switchgrass in replacing conventional fuels and biofuels (Samson et al., 2008)

Similarly, cellulosic ethanol derived from switchgrass results in net GHG offset up to 5,583 kg CO_2 eq ha^{-1} as compared to gasoline. Figure 2.2 show that switchgrass biofuel performs better than soybean biodiesel or corn ethanol in terms of GHG offset when replacing fossil fuels. This indicates that choice of biomass crops plays a vital role in overall environmental performance of biobased products.

A comparative study conducted on four different biomass crops for cumulative energy demand and the global warming impact revealed that switchgrass had less energy demand than corn and soybean (Kim and Dale, 2004). Also the global warming impact of switchgrass was found to be 50% and 13% less than corn and soybean, respectively. The weighted average values of cumulative energy demand and global warming impact of four different biomass crops are presented in Table 2.1.

Table 2.1. Cumulative energy potential and global warming impact of crops for production and transportation (data range for 7 different states of the USA) (Kim and Dale, 2004)

Crop	Cumulative energy potential MJ kg^{-1}	Global warming impact (gCO_2 eq kg^{-1})
Corn	1.99 to 2.66	246 to 286
Soybean	1.98 to 2.04	159 to 163
Alfalfa	1.24	89
Switchgrass	0.97 to 1.34	124 to 147

A study by the United State Department of Agriculture (USDA) revealed that switchgrass produce 540% more renewable energy than the energy used to grow and harvest the crop. Besides, average greenhouse gas (GHG) emissions from ethanol derived from switchgrass were 94% lower than estimated GHG from gasoline (Schmer et al., 2008).

2.3 An overview of switchgrass in Ontario and its cultivation practices

According to REAP Canada (Samson, 2007), switchgrass was grown in Ontario on about 283 ha with average yields of 8-12 t ha^{-1}. However, unpublished data indicates that the area under switchgrass cultivation in Ontario has increased to over 400 ha by now and this trend is likely to continue as new applications of switchgrass and related technology develops.

Under Ontario condition, maximum biomass production of switchgrass occurs during June-August. Cave-in-Rock is the most widely planted cultivar in North America. For northern Ontario, early maturing varieties like Forestburg, Sunburst, and Shelter show good result. A seed (pure live seed) rate of 8-10 kg ha^{-1} is found to be ideal for successful establishment. From the initial studies, biomass production was found to be 30% in the first year, 70% in the second year and attained full production potential (100%) in the third year onwards (Samson, 2007). Some of the Ontario's switchgrass production is being used for heating home and greenhouse operations, to offset natural gas and other fuels (McDonald and Banks, 2008). Although there is interest in growing switchgrass in Ontario, its production and business remains limited due to lack of well-developed market.

2.4. Life cycle assessment

2.4.1. Background on Life Cycle Assessment (LCA)

The initial studies on life cycle aspects of products and materials date back from the late sixties and early seventies and the major focus was on quantifying the material and energy consumption of a product (Bernstad et al., 2011).The 1970's oil crisis, energy debate and the environmental debate on waste disposal and packaging are considered to be the potential drivers behind the LCA (Baumann and Tillman, 2004). The first LCA study was conducted for the Coca-Cola in 1969 by Midwest Research Institute in the U.S. (Weidema, 1997; Heiskanen, 2000). The company was looking at the resource use and environmental impacts related to the packaging of their product in terms of environmental consequences of packaging manufacture, and alternative packaging materials. In 1972, Ian Boustead pioneered the LCA study on comparative energy demand of the beverage bottles in the UK (Baumann and Tillman, 2004). The Brent Spar debate on oil spill (1995-1996) highlighted the need to use LCA not only for consumer goods like detergents or consumer durables like washing machines, but also to major structures and installations (Bernstad et al., 2011). In the early 1990s, the United Nations earth summit recognized LCA as an environmental tool. There was a rapid increase attention in LCA during the 1990's and at the same time in 1993, J. B. Guine´e's first scientific publications on LCA come out (Finnveden et al., 2009). Since then, development and organization of LCA study has occurred which resulting in an international standard (ISO, 2006a, b) accompanied by a number of guidelines and textbooks (Baumann and Tillman, 2004; Wenzel et al., 1997). This has increased the maturity and methodological robustness of LCA (Finnveden et al., 2009). Currently there are several international initiatives that help to build consensus and provide recommendations. These Life Cycle Initiatives include the United Nations Environment Program (UNEP), the Society of Environmental Toxicology and Chemistry (SETAC; UNEP, 2002), the European Platform for LCA of the European Commission (2008b), and the International Reference Life Cycle Data System (ILCD). International Organization for Standardization (ISO 14040:1997) defined life cycle assessment (LCA) as the compilation and evaluation of inputs, outputs and potential environmental impacts of a product system. The term 'product' includes both goods and services (ISO, 2006a). LCA involves the evaluation of some aspects, often the environmental aspects of a product system through all stages of its life cycle. The life cycle of a product consist of different phases such as extraction of raw material, manufacturing, packaging, distribution, use and end of life of the product (Figure 2.3).

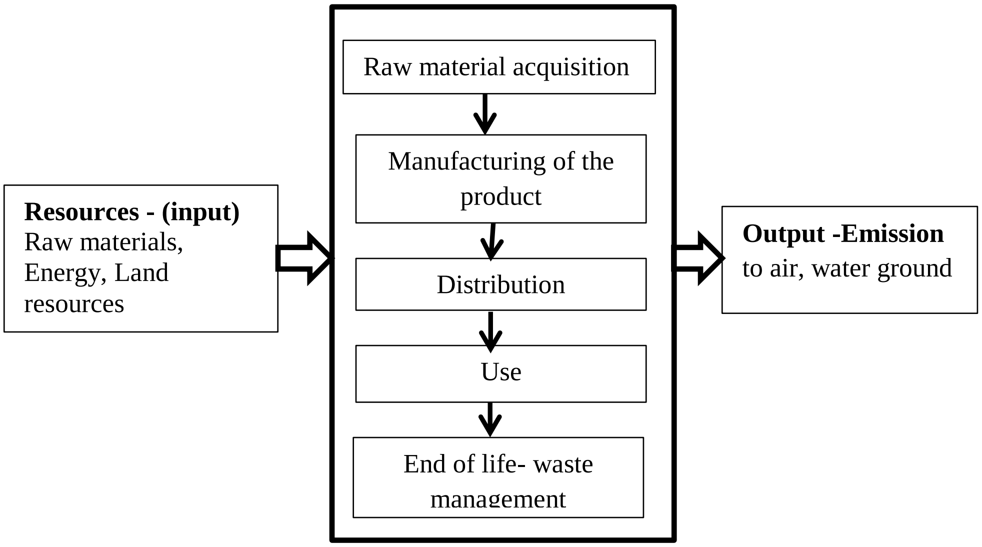

Figure 2.3. The life cycle model

2.4.2. Types of LCA

There are different types of LCA depending on the consideration of life cycle phases (boundary) and intended application (Baumann and Tillman, 2004). Based on the life cycle phases included in the LCA study, the most common LCA are *cradle to grave* and *cradle to gate* (Figure 2.4). The *cradle to grave* study includes resource extraction (cradle) to use phase and disposal phase (grave) of the product. The cradle to gate LCA includes resource extraction (cradle) to the factory gate (i.e., before it is transported to the consumer).

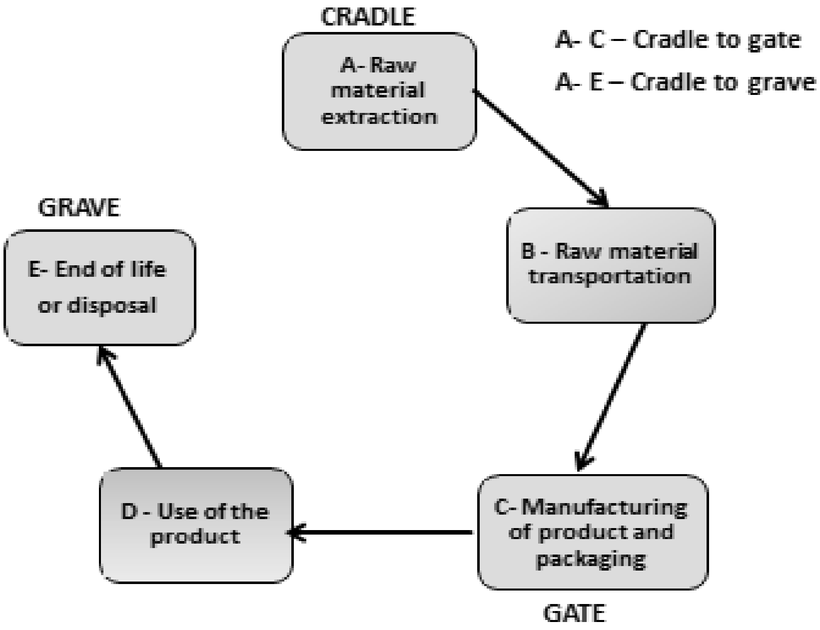

Figure 2.4. Types of LCA

Depending on the scope of the LCA, there are three general types of LCA studies (Baumann and Tillman, 2004):

1. The *accounting type LCA* is used to estimate a product's environmental impact, but also to compare different products.
2. The *change- oriented type LCA* is used for evaluating the best option among different possible scenarios.
3. The *stand-alone LCA* is the most common type and is the first, rough LCA conducted before any more detailed studies of a product/system are decided upon. It is an exploratory way to get acquainted with environmental characteristics of a product.

2.4.3. LCA Methodology

For LCA methodology, there is a series of international standards called ISO 14000 family developed by environmental experts from around the world under the auspices of the ISO Technical Committee 207. The ISO 14000 family comprises 4 different standards namely, ISO 14040:1997, ISO 14041:1998, ISO 14042:2000 and ISO 14043:2000 that explains four different phases in the life cycle assessment framework (Figure 2.5). The above ISO series have been revised and replaced by ISO 14044, together with ISO 14040:2006. According ISO 14044, there are four phases in an LCA study:

1. The goal and scope definition: Determination of life cycle stages, definition of unit processes and product system boundary

2. The inventory analysis: Data collection for input and output, modeling and analysis

3. The impact assessment: Assessment of potential impact using indicators

4. The Interpretation: Sensitivity analysis and quality check

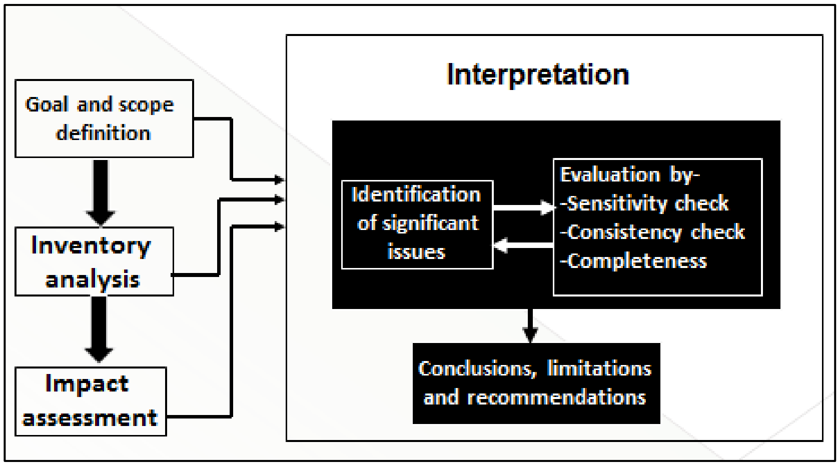

Figure 2.5. ISO 14040/14044: 2006 Life cycle assessment framework

2.4.4. Application of LCA

LCA is a tool that provides a better understanding of possible environmental impacts of a product, both manufactured and consumed (product includes services also) and helps in addressing these impacts. LCA can assist in:

-identifying opportunities to improve the environmental performance of products at various points in their life cycle,

-informing decision makers in industry, government or non-government organizations (e.g. for the purpose strategic planning, priority setting, product or process design or redesign),

-the selection of relevant indicators of environmental performance including, measurement techniques, and

-marketing (e.g. implementing an Eco labelling scheme, making an environmental claim, or producing an environmental product declaration

2.5. Life cycle assessment of crops

LCA was traditionally applied to analyse industrial production systems. However, over the last two decades, LCA has been adapted to assess the environmental effects of agriculture (Baumann and Tillman, 2004). Agricultural production practices used for crops significantly affect important environmental parameters and thus influence the environmental impacts of the crop production systems and its value chain.

Agriculture has been identified as one of the major contributors (14% in 2004 according to IPCC, 2007) to global GHGs. According to Environment Canada (2009), agriculture (crop and livestock) contributed 8% (56 Mt CO_2 eq) of Canada's total GHG emissions in 2009. However, methane and nitrous oxide are the major contributors to the total GHG (24% CH_4, 72% N_2O) in Canada. Besides GHG, agricultural production systems can potentially impact soil, water and biodiversity. Therefore, LCA is an important tool for evaluating such environmental impacts of agricultural production systems and find ways to reduce these impacts.

The bioeconomy adds value to agricultural crops, energy crops and crop residues by their use as feedstock for various bioproducts. This provides additional opportunities

to mitigate environmental impacts by replacing fossil fuels, where LCA plays key role in quantification of environmental impacts associated with the products.
A scan of relevant literatures on LCA of crops and bioproducts is presented with a summary of the key findings in Table 2.2.

LCA studies have been conducted on different crops around the world to understand environmental impacts of crop production systems and beyond farm gate. Corn, soybean, canola (*Brassica spps*.), sugarcane (*Saccharum officinarum)*, alfalfa (*Medicago sativa*), wheat (*Triticum aestivum*), hemp (*Cannabis sativa*) and energy crops like willow (*Salix spp*.), miscanthus, switchgrass are some of the important crops identified through this scan that have food, feed, fibre and ⁄ or bioenergy applications. Cradle to farm gate is the most common system boundary used for LCA studies involving agricultural production system. In these LCA studies, quantification of GHG and cumulative energy demand were major focuses. However, other impact categories (acidification, eutrophication, toxicity, ozone depletion) were also considered for crop production systems. In most LCAs, fertilization related processes and soil emissions were major contributors to the total environmental impacts of production systems (Biswas et al., 2008; Clair et al., 2008; Gallego et al., 2011; Kim and Dale, 2004; Kim and Dale, 2005; Pelletier et al., 2008). Leguminous crops like soybean and alfalfa showed less soil emission due to less nitrogen fertilizer application.

Comparative LCA of perennial and annual crops revealed that perennial crop production systems, primarily energy cropping showed less environmental impacts than most annual cropping systems (Clair et al., 2008; Kim and Dale, 2004; Monti et al., 2009). Among different perennial crops (switchgrass, miscanthus, reed canary grass and cyanara), switchgrass performed better in global warming potential (GWP), eutrophication, toxicity and ozone depletion (Monti et al., 2009).

When carbon sequestration and cover cropping were considered in the LCA, the total environmental impact of crop production systems was reduced (Cherubini and Jungmeier, 2009; Adler et al., 2007; Kim and Dale, 2005). A few studies were conducted using a cradle to use phase boundary for switchgrass based bioproducts (Bai et al., 2010; Spatari et al., 2005). The result revealed that switchgrass based bioethanol (E85) performed better in terms of GWP compared to gasoline; however no significant reduction was observed for other impact categories (acidification, eutrophication and toxicity) (Bai et al., 2010). In the same study, agricultural practices were found to be main contributors to eutrophication, acidification and toxicity. In another study (Spatari et al., 2005), automobiles fueled with switchgrass derived ethanol (E85) showed 57% lower GHG emissions than that of low sulphur reformulated gasoline.

Table 2.2. Life cycle assessment of different crops

Author and Location	Crops	System Boundary; Functional Unit	Goal (G) and Key Findings (KF)
Monti et al., 2009. Italy	Switch grass, miscanthus, giant reed, cyanara.	Cradle-to-farm gate; ha and Energy (GJ)	**G:** To compare the environmental impacts of four perennial energy crops and to quantify the ecological benefits of replacing conventional crops with energy crops. **KF**: Among the bioenergy crops on hectare basis switchgrass was the best performing crops in six different impact categories (toxicity, eutrophication, ozone layer depletion and global warming potentials). Besides, the energy crops showed 50-60% lower impact, by substituting the conventional rotation (wheat-maize) with perennial crops.
Heller et al., 2003 USA	Willow	Cradle-to-farm gate; 1 ha	**G:** Analysis of the energy performance and net GHG emission of willow biomass production system **KF:** Generating electricity from a willow biomass crops could produce 11 units of energy per units of fossil energy consumed and contributed additional environmental benefits.
Van der Werf, 2004 France	Fibre hemp	Cradle-to-farm gate; 1 ha	**G:** Quantify the environmental impacts associated with field production of fibre hemp and to compare the impacts of hemp to other annual crops. **KF:** Relative to other crops of this study, hemp and flax were low-input and low-impacts crops; whereas potato and sugar beet were high-input and high-impact crops. A comparison of hemp (low impacts), wheat (intermediate impacts) and sugar beet (high impacts) revealed that the crops were similar for the relative contributions of emitted substances of processes to impacts. A reduction of the impacts of hemp production should focus on eutrophication, and consider the impact on climate change, acidification and energy use as secondary objectives. Besides reduced tillage was found to be effective to reduce the energy use, acidification and climate change impacts.

Pelletier et al., 2008 Canada,	Corn, Canola, Soybean, Wheat	Cradle-to-farm gate; 1 kg	**G:** Generate basic life-cycle models of existing conventional and organic crop production systems in Canada **KF**: Total transition from conventional to organic production of these crops in Canada would reduce national energy consumption by 0.8%, global warming emission by 0.6%, and acidifying emissions by 1.0%. Organic crop production system was found to have less energy demand and produce lower emissions for all the impact categories analysed in this study. Fertilizer production was the prime contributor of cumulative energy demand for conventionally produced crops whereas fuel consumption was major contributor of cumulative energy for organic crops.
Clair et al., 2008 UK	Short rotation coppice (SRC), miscanthus, oil seed rape (OSR)	Cradle-to-farm gate; 1 ha	**G**: Assessment of pre-harvest GHG costs of production of SRC, miscanthus, and OSR, when compared to a range of former land use baselines. **KF:** GHG costs were very low for miscanthus and SRC but higher for OSR production, determined mainly by the need for nitrogen fertilization. Former land use was of critical if energy crops were a net source or sink of GHGs. Converting to SRC and miscanthus were the most favourable energy crops in terms of GHG savings. Converting to OSR from arable cropping resulted in either small increases or decreases in GHG emissions, depending upon the former tillage practices on the arable land , but replacing either broadleaved woodland with OSR (mainly due to soil carbon loss and increased fertilizer related NO_2 emissions) or grassland with OSR (mainly due to soil carbon loss) greatly increases emissions**.**
Kloverpris et al., 2009 USA and Canada	Corn and Canola	Cradle-to-farm gate; 1 tonne	**G**: To compare conventional production of Corn in the USA and Canola in Canada with production of the same crop seeded with the yield enhancing microbe *Penicillium bilaii* **KF**: Environmental impact from crop production could be significantly reduced and resources like fossil fuels, agricultural lands and phosphorus could be saved by using *Penicillium bilaii (* Jumpstart)

Kim and Dale, 2005 USA	Corn and soybean	Cradle-to-farm gate; 1 ha	**G**: A life cycle assessment of different cropping systems emphasizing corn and soybean production was performed; assuming that biomass from the cropping systems is utilized for producing biofuels (i.e., ethanol and biodiesel). **KF**: Non-renewable energy consumption, global warming impact, acidification and eutrophication were considered as potential environmental impacts. When biomass from the cropping systems was utilized for biofuel production, all the cropping systems studied offered environmental benefits in terms of non-renewable energy consumption and global warming impact. Therefore utilizing biomass for biofuels would save non-renewable energy, and reduce greenhouse gases. However, unless additional measures such as planting cover crops were taken, utilization of biomass for biofuels would also tend to increase acidification and eutrophication, primarily because large nitrogen (and phosphorus)-related environmental burdens were released from the soil during cultivation.
Kim et al., 2009 USA	Corn grain and corn stover	Cradle-to-farm gate; 1 kg dry biomass	**G**: To estimate environmental performance for continuous corn cultivation of corn grain and corn stover grown for various corn growing locations in the US Corn Belt. **KF**: Corn stover had a better environmental performance than corn grain for all environmental impacts considered. It was due to lower consumption of agrochemicals and fuel used in the field operations and lower nitrogen-related emissions from the soil. The primary source of total fossil energy associated with biomass production was nitrogen fertilizer, accounting for over 30% of the total fossil energy. Nitrogen-related emissions from soil (i.e., N_2O, NO_x, and NO_3 leaching) were the primary contributors to all other life cycle environmental impacts.
Biswas et al., 2008 Australia	Wheat	Cradle-to-post farm gate storage; 1 tonne	**G:** The goal was to estimate the total GHG emitted during the production of rain-fed wheat. **KF:** The GHG emission during the production and delivery of 1 tonne of wheat to port was equivalent to 304 kg CO_2, which was 38% less than the value

		wheat transported to port	calculated when using the IPCC emission factor for N_2O. The pre-farm stage, which included environmental impact of the production of inputs, such as mining, processing and transportation to the point of use, accounted for the significant portion (45%) of the total global warming potential, followed by on-farm (44%) and post-farm (11%) stages. The production of fertiliser accounted for a significant portion (35%) of the impact for pre-farm and on-farm activities for wheat production, while GHG emissions from transportation were found to be predominant during the post-farm stage. Specific regional data for soil N_2O emissions should be used rather than international default values, when assessing GHG from agricultural production systems.
Gallego et al., 2011 Spain	Alfalfa	Cradle-to-farm gate; 1 tonne dehydrated alfalfa at 11% moisture	**G:** To evaluate the environmental burdens associated with the cultivation and dehydration of alfalfa. **KF:** Among the life cycle processes of alfalfa, the dehydration process, production of phosphate and nitrogen fertilizer and pesticides, water consumption and final transport to the consumer (by road and ship) were identified as hotspots.
Cherubini and Jungmeier, 2009 Norway	Switch grass	Cradle-to-use phase; Amount of biomass treated per year in biorefinery (i.e. 477 kt dry biomass per day).	**G**: LCA of a biorefinery producing bioethanol, electricity, heat, and chemicals (phenols) from switchgrass. **KF**: The use of switchgrass in biorefinery offsets GHG emissions and reduced fossil energy demand in comparison to the fossil reference system producing the same product/ services from fossil resources. The result shows that GHG emission was decreased by 79% and 80% of the non-renewable energy was saved. The switchgrass production contributed the most to the GHG emission of the system due to high nitrous oxide emission. However, large GHG benefit comes from soil carbon sequestration (65 kt CO2-eq/a, for the first 20 years) of switchgrass. The results of other impact categories (eutrophication and acidification) were found to be higher in biorefinery system.
Adler et al., 2007	Switch grass,	Cradle-to-farm gate;	**G**: Quantification of net effect of several bioenergy crop production systems on greenhouse gas (GHG)

USA	corn, soybean, alfalfa, hybrid poplar and reed canary grass.	1 ha	emission. **KF**: All cropping systems considered provided net GHG sinks, even when soil C was assumed to reach a new steady state and carbon sequestration in soil was not counted. Hybrid poplar and switchgrass provided the largest GHG sinks (>200 g CO_2 eq-C.m^{-2}.yr^{-1}) for biomass conversion to ethanol, and >400 g CO_2 eq-C.m^{-2}.yr^{-1} for biomass gasification for electricity generation. Compared with the life cycle of gasoline and diesel, ethanol and biodiesel from corn rotations (i.e. growing other crop than corn) reduced GHG emissions by around 40%, 85% and 115% for reed canary grass, switchgrass and hybrid poplar, respectively.
Bai et al., 2010 The Netherlands	Switch grass	Cradle-to-use phase; Power to wheels for 1-km driving of a midsize car	**G**: Assess the environmental impact of using ethanol from switchgrass as transportation fuel and to compare the results with gasoline to analyze the potential of developing switchgrass ethanol as an environmentally sustainable transportation fuel. **KF**: Switchgrass ethanol fuel (E85, a blend of switchgrass ethanol to gasoline) reduced GHG emission by 65% over gasoline and thus reduced the global warming potential (GWP). Except for GWP and resource depletion, switchgrass ethanol did not offer environmental benefits in the other impact categories (acidification, eutrophication and toxicity) compared to gasoline. Agricultural practices were found to be main contributors to eutrophication, acidification and toxicity. Improvements in switchgrass yield and ethanol production technologies were important considerations to lowering environmental impact in future.
Spatari et al., 2005 Canada	Switch grass and corn stover	Cradle-to-use phase; Gram of CO_2 equivalent per kilometer	**G**: To assess the environmental implications of the production and use of ethanol in automobiles. The environmental performance of automobiles fuelled with cellulose-derived E85 and low sulphur (30 ppm) reformulated gasoline (RFG) were estimated for two time frames, near (2010) and mid-terms (2020). **KF**: Near term results showed that compared to a low sulphur reformulated gasoline (RFG) automobile, life cycle GHG emissions were 57%

			lower for an E85 fuelled automobile derived from switchgrass and 65% lower for ethanol from corn stover, on a gram of CO_2 equivalent per kilometer basis. Midterm scenario showed that GHG emissions could be 25-35% lower than those of near term results and E85 automobiles could achieve up to 70% lower GHG emission across life cycle.
Qin et al., 2006 USA	Switch grass	Cradle-to-use phase; 1 kg switchgrass and 1 kilowatt hour	**G**: Life cycle assessment of integrated environmental, energy, economic and technological implications of using switchgrass to replace coal in power generation. **KF**: The most effective technologies for switchgrass preparation were harvesting loose materials for hauling and chopping and then compressing it into modules and transporting. The GHG mitigation per ton of switchgrass used during co-firing was better than switchgrass fired alone with the GHG effects of 68.5 g CO_2 eq kw h^{-1} for switchgrass fired alone and 50.4 g CO_2 kw h^{-1} for 10% switchgrass co-fired with coal.
Meisterling et al., 2009 USA	Wheat	Cradle-to-use phase; 1 kg	**G**: A streamlined hybrid LCA to compare the global warming potential (GWP) and primary energy use of conventional and organic wheat production and delivery in the US. **KF:** The GWP of a 1 kg loaf of organic wheat bread was about 30 g CO_2 equivalent less than the conventional loaf. When organic wheat was shipped 420 km farther to market, the organic and organic wheat systems had similar impacts. These results could change dramatically depending on soil carbon accumulation and nitrous oxide emissions from the two systems.
Kim and Dale, 2004 USA	Corn, soybean, alfalfa, switch grass	Cradle-to-use phase; 1kg	**G:** To determine the cumulative energy requirement and global warming impact from the production of biomass for biobased products. **KF**: For corn and switchgrass, nitrous oxide was the major contributor (50%) to the total GWP. For soybean and alfalfa (leguminous crop with low nitrogen requirement), CO_2 contribute major (80%) of the GWP. Fertilizer and agrochemical production, diesel used for field operation and transportation were the major sources of primary energy use.

This review of the literature shows that there are limited studies available on comprehensive life cycle assessment of perennial energy crops in regards to environmental impacts of cultivation practices. Also, in many agricultural LCA studies where the methodology has been used to address the impact of the bio refining industrial process, the applications of cultivation processes are considered secondary (Monti et al., 2009). In contrast, some studies revealed that cultivation has significant impact on the life cycle of the biomass derived fuel (Bai et al., 2010; Gasol et al., 2007; Kaltschmitt et al., 1997). Kim and Dale (2004) reported that agricultural processes account for a large fraction of the total energy consumption in producing biobased products. A better understanding of the agricultural practices is essential to improve the environmental performance of the biomass crops and biobased products as well. Therefore, life cycle assessment of perennial crops like switchgrass with major emphasis on Ontario agricultural practices is necessary for better understanding of environmental impact of the crop, and to make decisions about its higher value added applications in different biobased industries.

Based on this background, perennial grasses like switchgrass is found to be less input intensive and require less agronomic practices and thus the energy use and environmental impacts of switchgrass biomass production should be lower than most annual biomass crops.

CHAPTER 3

MATERIALS AND METHODS

3.1 Type of Life Cycle Analysis or Assessment (LCA)

The purpose of the present LCA study is to understand the environmental profile of switchgrass biomass production (chopped biomass) in Ontario and also to identify which processes cause the greatest environmental impact. Therefore, a stand-alone attributional LCA is considered for this study. The stand-alone LCA is the most common type of LCA (Frankl and Rubik, 2000) and it provides the basis for more detailed studies. Moreover, an attributional LCA is applicable for understanding the emissions directly associated with the life cycle of a product (Brander et al., 2008).

3.2 Goal and scope definition phase

This phase defines the "product" (switchgrass biomass) of this LCA, its functional unit, system boundary, data collection methods and the intended audience of the results.

3.2.1 Goal of the study

The goal of this study is to quantify the environmental impacts and energy use of switchgrass biomass production (chopped biomass) in Ontario. The objectives of this study are not to compare the results with other systems or references, rather it is meant to provide insight into the potential environmental impacts and energy use of switchgrass production practices.

This study has been performed in accordance with the guidelines of the International Organization of Standardization (ISO 14040, ISO 14044, 2006) for the life cycle assessment. The SimaPro7.3.2 software developed by Product Ecology Consultants (PRé Consultants, Amersfoort, Netherlands) was used to model life cycle inventory (LCI) and analyse the environmental impacts.

This is an internal screening (LCA for internal communication purpose and without external review) LCA study of switchgrass for the Bioproducts Discovery and Development Center, University of Guelph. The Centre has successfully utilized switchgrass fibre for production of biocomposites. This is the first phase of study upon which life cycle assessment for the switchgrass-based biocomposites can be modelled.

The intended application of this LCA is to get a better understanding of the environmental performance of switchgrass biomass production. The LCA results could be useful to better understand the environmental impacts of using switchgrass biomass for biocomposite application. The results are mainly intended for use by researchers (agronomist, breeder, bioproduct engineer); however, will also be beneficial for informing switchgrass farmers and policy makers in Ontario about management practices and environmental issues.

3.2.2 Function and Functional unit

The function of this system is to produce switchgrass biomass; therefore the functional unit for this study is 1000 kg (1t) of chopped biomass production from a 10 year production cycle. The mass based functional unit seems to be in agreement with other agricultural LCA studies (González-García et al., 2010; Ramjeawon, 2004).

Once planted, switchgrass remains productive at least up to 10 years with a total cumulative production of 90 t from 1 hectare (1 cut or harvest per year with 10t ha^{-1} yield) in ten years. The average production is lower in the first year (30% of mature production) and the second year (70%) until it attains full production potential from third year onwards (Samson, 2007).

3.2.3 Allocation

Many (production) processes perform more than one function or output. Therefore, the environmental load of those processes needs to be allocated over the different functions and outputs for life cycle analysis. In the present study, no allocation is considered in the process of switchgrass biomass production because biomass is the only output or product of this process.

3.2.4 System boundary and system description

Environmental evaluation of an agricultural system should consider impacts of all the field operations (on-farm process) and impacts related to the production and transportation of the system inputs (González-García et al., 2010). In this study, the system boundary of switchgrass biomass production was considered from cradle-to-farm gate. The base case scenario assumes the production cycle of switchgrass as 10 years (perennial crop) with a single harvest each year and the full yield potential of the crop is attained from third year after planting. Figure 3.1 is a schematic presentation of the switchgrass biomass production system boundary. The boundary included on-farm unit processes in the first year (land preparation, weed burn down and planting seeds), operations in the second year (mowing, herbicide application, fertilization, harvesting, baling and chopping) and crop maintenance operations during 3rd to 10th year (mowing, fertilization, harvesting, baling and chopping) in addition to related upstream processes. The upstream processes considered in this study were the production and transportation of diesel fuel, fertilizer, and herbicides and switchgrass seed. However production and transportation of farm equipment were not included in the system boundary because literature suggested that these had small contribution to the overall impact (Graboski, 2002).

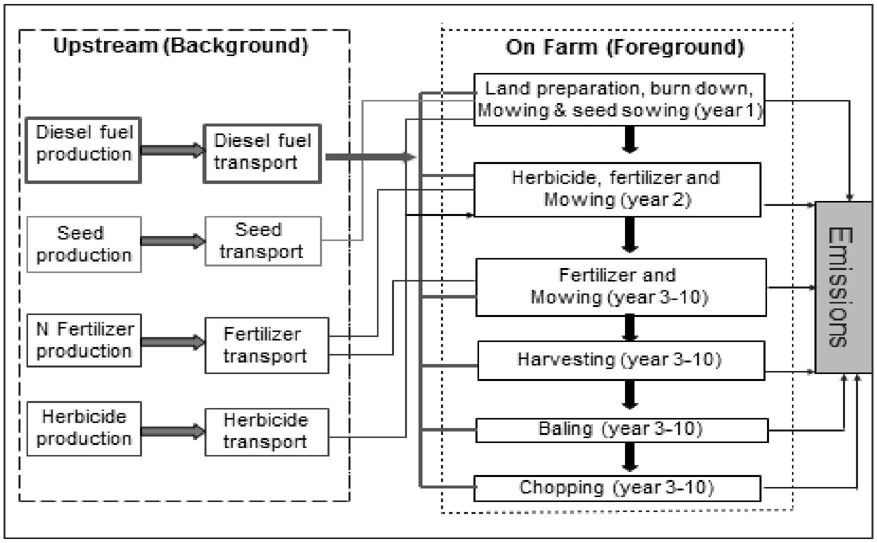

Figure 3.1 System boundaries for switchgrass LCA

The first year on farm processes of switchgrass production involve weed burn down, land preparation (ploughing twice), land packing, seed sowing, followed by another land packing. These soil management processes are only implemented in the first year. Weed control is a major challenge in the first two years of switchgrass planting. The establishment of switchgrass can be improved by cultural as well as mechanical weed control measures. Herbicide application in the first two years of planting and mowing are the methods adopted for controlling weeds in switchgrass. No fertilizer is applied in the first year of switchgrass planting to avoid weed competition. In second year of the switchgrass life cycle, nitrogen fertilizer is used however no phosphorous and potash fertilizer is recommended unless the soil is too low in phosphorous (less than 10 ppm) and potash (less than 80 ppm). No herbicide is applied to switchgrass from third year onward. The soils of switchgrass growing farm are in general sandy loam to clay loam. Switchgrass is fully established after completion of second year and can produce maximum biomass from third year onward.

In this study, two commercially adopted harvest systems were considered and modelled separately (Figure 3.2). Depending on storage options, harvest equipment and market, farmers may adopt any of the two different harvest systems as describes below.

Harvest system 1 (HS 1): Switchgrass field is harvested by swathing (windrower) in the fall followed by raking in the following spring and chopped thereafter by using forage harvester. The chopped biomass is then transported in bulk using a forage wagon and stored. From swathing to storage, HS1 has five processes as depicted in Figure 3.2.

Harvest system 2 (HS2) : Switchgrass field is harvested by swathing (windrower) in the fall followed by raking in the following spring and baling by using a large round or square bailer after the swath is dry. The bales are then loaded by tractor bale loader and transported to the storage area. The bales are chopped at 2-4 cm length by using a tub grinder. From swathing to storage, HS2 has six processes (Figure 3.2).

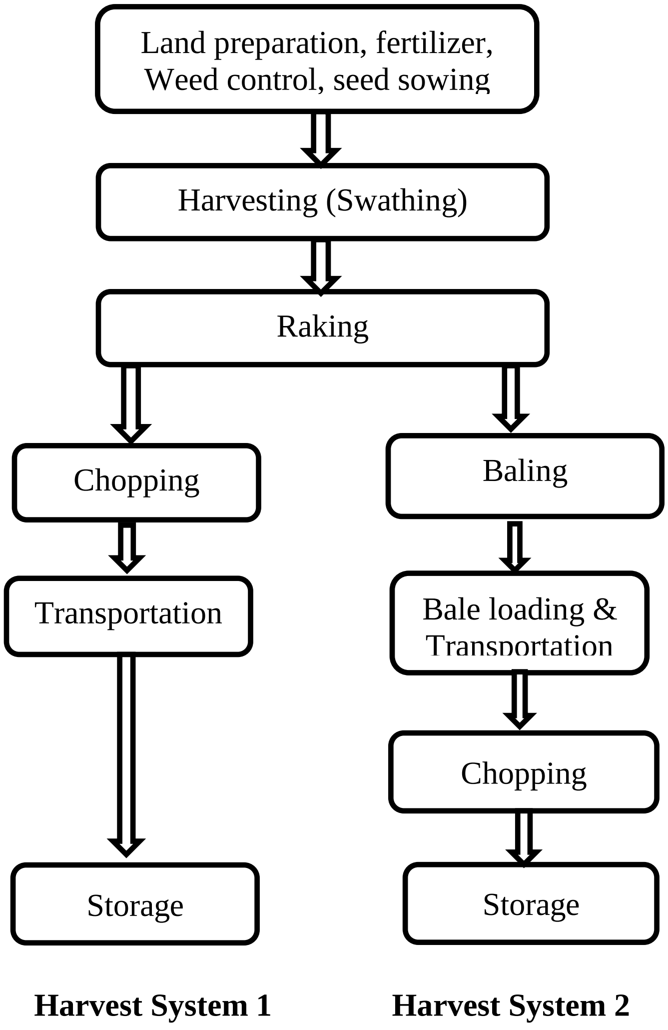

Figure 3.2 Two different harvest systems (HS1 and HS2)

3.3 Life cycle inventory (LCI) phase

This phase included: 1) data collection for the foreground processes (on farm) and background processes (upstream) as defined in the system boundary and, 2) calculation of the amount of resource (input e.g. diesel, herbicides, fertilizer) use and pollutants emissions (output) of the system in relation to the functional unit.

3.3.1 Data collection

Foreground data: For switchgrass life cycle inventory, on-farm data (foreground data; Figure 3.1) for switchgrass cultivation practices were collected from three different switchgrass farms in Ontario through survey questionnaire, interview and follow up communication. Among these farms, Don Nott Farm in Clinton (southern Ontario) is the pioneer in switchgrass cultivation in Ontario (growing for the last six years) and has about 148 ha of switchgrass plantation. The other farms were smaller (under 20 ha). Besides, the smaller farms were lacking well documented information on the cultivation practices. Therefore, switchgrass LCI was developed using the Don Nott farm data and available literature on switchgrass management guide for Ontario (Samson, 2007).

Data were collected for types of machinery used in various field operations, hours of operation, amount of diesel fuel used, application rate of various inputs (seed, fertilizer, herbicides) for field operations. The collected field data of the agronomic practices have been validated by professionals (Scott Banks, Emerging Crop Specialist) of Ontario Ministry of Agriculture and Rural Affairs, and through available literature. These foreground data represent base case scenario for Ontario switchgrass production.

The data on field operations and inputs related to switchgrass cultivation are presented in the Tables 3.1 and 3.2, respectively.

Table 3.1. Field operation data (machinery and fuel use) for switchgrass cultivation

Year	**Operation/ process**	**Tractor & equipment used**	**Fuel used**
1	Land preparation-plough	225 HP tractor for disk plough-2 passes	7 L/ha
1	Land preparation-packing	100 HP Cultiupacker-1 pass	2.3 L/ha
1	Herbicide application (Burn down)	160 HP Boom Sprayer	1.25 L/ha
1	Seed sowing	160 HP Seed driller	2.8 L/ha
1	Field packing after sowing	100 HP Cultipaker-1 pass	2.3 L/ha
1-2	Herbicide application	160 HP Boom Sprayer	1.25 L/ha
2-10	Fertilizer application	100 HP tractor spreader	2.3 L/ha
1-10	Mowing (weed control)	160 HP tractor	2.2 L/ha
1-10	Swathing	160 HP tractor New Holland windrower	7.81 L/ha
1-10	Raking	70 HP swath turner	4.3 L/ha
1-10	Baling	225 HP tractor bailer	16 L/ha
1-10	Chopping (HS1)	225 HP forage harvester	8.5L/t
1-10	Chopping (HS2)	225 HP tub grinder	8.0 L/t
Data source: Don Nott farm, Clinton, Ontario; Samson, 2007			

Background data: The data for upstream processes (diesel fuel production, agro-chemicals and seed production) were taken from US-EI database from SimaPro software.

Table 3.2. Agricultural input and output data for switchgrass production

Year	**Input/output**	**Input/output rate**
1	Herbicide (Burn down)	Glyphosate 1.2 kg active ingredient ha^{-1}
1	Seed rate	10 kg pure live seed ha^{-1}
1-2	Herbicide	Atrazine 1.1 kg ai ha^{-1} 2,4-D 1.0 kg ai ha^{-1}
2-10	Nitrogen Fertilizer	55 kg N ha^{-1}
1-10	Biomass yield- 1 cut per year Moisture content in dry biomass: 10-12%	Annual yield: Year 1 : 3 t ha^{-1} Year 2 : 7 t ha^{-1} Year 3-10 : 10 t ha^{-1}
	Energy content in switchgrass	18.5 GJ t^{-1}
Data source: Don Nott farm, Clinton, Ontario; Samson, 2007		

Table 3.3. Emission factors and sources

Process	Emission factors	Source
Diesel combustion (Farm equipment)	CO_2= 2.663kg L^{-1} diesel CH_4=0.00014kg L^{-1} diesel N_2O=0.0001kg L^{-1} diesel	Greenhouse Gas Division, Environment Canada, August 2004.
	Other emissions	Ecoinvent database
Soil N_2O emission	0.017 kg N_2O-N kg^{-1} N input	Rochette et al., 2008
Soil NH_3 emission	Calculated based on 6% of applied fertilizer N	Sheppard et al., 2010
Fertilizer, herbicide related	All emissions	Ecoinvent database

3.3.2 Use of field operations data.

On-farm operations such as ploughing, land packing, seed sowing etc. generate emissions linked to fuel combustion, resource consumption and environmental impact from machinery use in agricultural processes (Blengini and Busto, 2009). For this study, Ontario specific data (Table 3.1) on machinery, equipment, other inputs (Table 3.2) were used to integrate in the general agricultural operations described in US-EI database (modified from Ecoinvent database, Nemecek and Kagi, 2007) to prepare the LCI. The data for manufacturing processes for diesel fuel, ammonium nitrate, glyphosate, 2, 4-D and atrazine were taken from the US-EI database.

Two means of transport were considered within the system boundaries (Figure 3.1), all of them have been included by means of similar processes described in the US-EI database which was modified with US electricity from the Ecoinvent 2.0 database (Spellman et al., 2007). The transportation of seeds, fertilizers and herbicides from regional storehouse to the farm (average distance assumed was 10 km) is made by small pick-up truck (<3.5 t). For transportation of diesel fuel, an average distance of 80 km from the regional diesel plant to the farm to procure fuel for different farm activities was assumed.

3.3.3 Data quality and variability

The data used in this model are obtained from primary data sources (farm data) which are representative of switchgrass production practices in Ontario during the time horizon 2006-2011. However, some variability exists for the yield data for different farms and sensitivity analysis was undertaken to study these yield variability.

3.3.4 Calculation of input and output

Based on the on farm data (input) for various switchgrass production operations (processes), the activity levels (input required for producing 1 t of switchgrass biomass) were calculated (Table 3.4). Calculation of activity levels is based on resources used for 0.011ha of land area that produces 1t of switchgrass biomass in 10 years. The activity levels were then multiplied by emission factors (Table 3.3) for different inputs (diesel, fertilizer, seed and pesticides) to quantify the total emissions associated with each input and operation. The Canadian emission factors for GHG emissions (carbon dioxide, methane and nitrous oxide) were taken from Environment Canada (Table 3.3). However, for the other environmental emissions (e.g. sulphur dioxide, chlorofluorocarbon, and nitrogen dioxide) emission factors were used from US-EI databases as there is no Canadian emission factor available for these emissions.

Synthetic nitrogen fertilizer contributes to soil emissions and soil emission rates vary based on the soil type, climatic conditions and agricultural practices. The emission of nitrous oxide (N_2O) from agricultural soil also contributes to global warming and depletion of the ozone layer. In this study, the emission of N_2O from agricultural soil was considered and was calculated based on the methodology developed by Rochette et al. (2008). The regional fertilizer induced emission factor for Ontario is 0.017 kg N_2O-N kg $^{-1}$ N. Also ammonia (NH_3) emission related to nitrogen fertilizer was also accounted in this study and the emission factor was used as described by Sheppard et al. (2010). This study indicates that 6% of the applied fertilizer N is lost as NH_3 gas. Nitrous oxide emissions due to the decomposition of crop residues and of fixed nitrogen were not included in this study as decomposition of crop residues and nitrogen fixed by biomass depends on subsequent crop systems. These emissions are very specific to location.

Soil carbon sequestration was excluded in this study as there is no carbon sequestration data for switchgrass in Ontario published yet. However, soil carbon sequestration impacts will be discussed in Chapter 5.

Table 3.4. Activity levels for production of 1000 kg (1t) switchgrass for 10 years

Inputs for switchgrass production process	***Activity levels (input per functional unit)**
Fuel used for land preparation	0.136 L
Fuel used for application of herbicide	0.069 L
Fuel used for seed sowing	0.040 L
Fuel used for mowing (weed control)	0.481 L
Fuel used for harvesting (Swathing)	0.228 L
Fuel used for baling	1.540 L
Fuel used for chopping	0.842 L
Switchgrass seed	0.110 kg
Glyphosate	0.013kg ai
2,4 D	0.022kg ai
Atrazine	0.024kg ai
Ammonium nitrate (contain 35% N)	15.55 kg

**Activity levels were calculated assuming an average annual yield of 10 t (10-12% moisture) switchgrass biomass in 10 years per hectare. To produce 1 t switchgrass (functional unit) in 10 years, different inputs are calculated for 0.011 ha land.*

In the LCI phase, a model was developed in SimaPro 7.3.2 by quantifying total resources and emissions associated in all processes (as shown in system boundary, Figure 3.1) of switchgrass cultivation. The model was used to analyze and assess environmental impact of processes, as described in the life cycle impact assessment phase below.

3.4 Life cycle impact assessment (LCIA) phase

The LCIA phase aims at describing the consequences of environmental loads quantified in the LCI (Baumann and Tillman, 2004). In other words, the impact assessment provides further interpretation of the LCI data. The inventory data are multiplied by characterization factors to give indicators for the environmental impact categories. This phase translates the LCI results (environmental loads) into environmental impacts (Figure 3.3). According to ISO standard, there are two distinct elements in the impact assessment:

- Obligatory elements: Definition of impact categories, classification and characterisation
- Optional elements: normalisation, ranking, grouping and weighting.

Every LCA must at least include classification and characterisation (Baumann and Tillman, 2004).

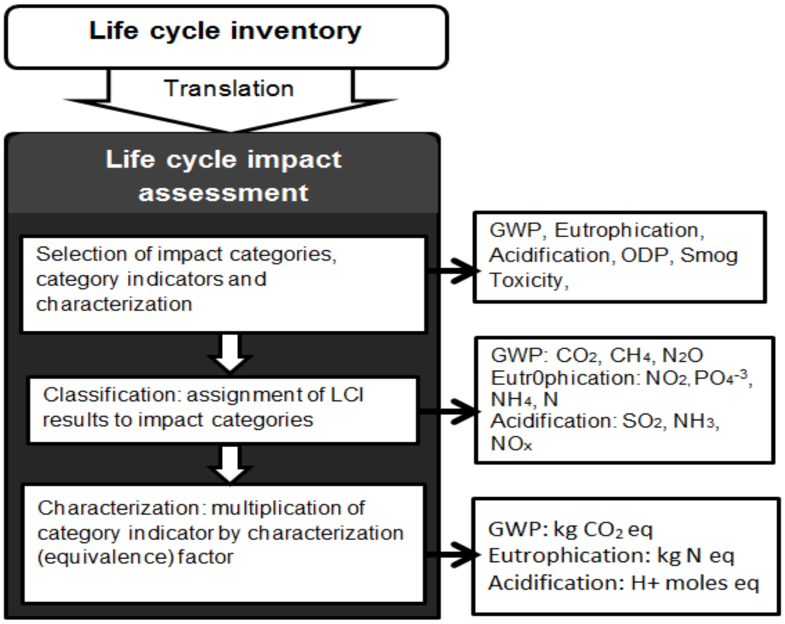

Figure 3.3. Relationship between inventory analysis and different phases of life cycle impact assessment (LCIA)

The obligatory elements were only considered that would be adequate for the goal and scope of this study namely to assess the environmental impact as well as identify emission hot spots of switchgrass production. In order to perform impact assessment, two methods were selected that are described below. The readymade LCIA methods (TRACI 2 and Cumulative energy demand) from the SimaPro software were used for characterization of the life cycle inventory results. Following sub phases were involved in this impact methodology.

1. Selection of impact categories, category indicators & characterization models: Based on the goal of this study, the impact categories shown in Table 3.5 were selected to understand environmental impacts of switchgrass production.

Table 3.5. Impact categories and units.

Impact category	**Unit**
Global warming	kg CO_2 eq
Acidification	H+ moles eq
Respiratory effects	kg $PM_{2.5}$ eq
Eutrophication	kg N eq
Ozone depletion	kg CFC-11 eq
Ecotoxicity	kg 2,4-D eq
Smog	g NO_x eq
Carcinogenics	kg benzene eq
Non carcinogenics	kg toluene eq

2. Classification: The LCI results are sorted and assigned to the various impact categories. Some parameters (e.g. NO_x) need to be assigned to more than one category.

3. Characterization: It involved calculation of category indicator results using characterization factors. In the characterization phase, emissions contributed to an impact category were multiplied by a characterization factors that expressed the relative contribution of the substance. The characterisation factors are specific for each of the impact category. For example, in Global warming potential for 100 years the characterization factor for CO_2 is 1, while for methane it is 23, and for N_2O the factor is 298. In acidification, the characterisation factor for SO_2 is 1 while for $NH_{3,}$ it is 1.88.

The following methods were selected to quantify energy use (Cumulative energy demand) and environmental impacts associated with switchgrass biomass production.

a) Cumulative energy demand: This method characterizes the different energy demand into non-renewable and renewable energy (Frischknecht et al., 2003). For the present study, cumulative energy demand was quantified following the cumulative energy demand method version 1.08 in SimaPro.

b) TRACI 2 (Tools for the Reduction and Assessment of Chemical and other environmental Impacts version 2): This method was developed by Environmental Protection Agency (EPA, U.S.) for North American applications with input parameters consistent with U.S. locations. TRACI 2 is a method that uses the midpoint approach and thus has the obligatory elements only (classification and characterization).TRACI 2 facilitates the characterisation of the environmental stressor under different potential effects (midpoint) namely, ozone depletion, global warming potential, acidification, eutrophication, photochemical oxidation (smog), ecotoxicity, human health (respiratory effects, carcinogen and non-carcinogen) (Bare et al., 2002; Bare et al., 2006; Frischknecht et al., 2007). A short description of the nine impact categories used for this study is given below.

- Global Warming Potential: The potential contribution of a substance to climate change is expressed as its global warming potential. The global warming potential of a substance is defined as the ratio between the increased infrared radiation it causes and the increased infrared absorption caused by 1 kg carbon dioxide (Bauman and Tillman, 2004). Greenhouse gases like carbon dioxide, methane, nitrous oxide absorb radiation at various degrees and hence their ability to heat the atmosphere. The GWP 100 years (kg $CO_{2\ eq}$) for carbon dioxide is 1 which is much lower than methane (23) and nitrous oxide (298).
- Acidification: Acidifying pollutants like sulphur dioxides, nitrogen oxides, hydrochloric acid and ammonia in water cause fish mortality, leaching of toxic metals out of soils and rock, and damage forests and buildings. The acidification potential is the number of hydrogen ions produced per kilogram of substance relative to sulphur dioxide and is expressed in H+ moles eq. The capacity to form hydrogen ions is the basis for characterization modeling in LCA.
- Ecotoxicity: The substances (such as zinc, nickel, lead, cadmium) in this category are toxic to flora and fauna in soil, air and water. Its unit of measurement is kg 2, 4-D equivalent.

- Eutrophication: Higher levels of nutrient leaching particularly nitrogen and phosphorus in water bodies lead to higher oxygen demand (useful for LCA characterization modeling) through shifting species composition and increased biological productivity. The unit of measurement is kg N equivalent.
- Human Toxicity*:* This category describes and measures the impact of toxic substances on human environment that can be further subdivided into i) *Human health cancer*: measured in kg benzene equivalent, ii) *Human health non-cancer*: measured in kg toluene equivalent, and iii) *Human health criteria air pollutants (respiratory effect)*: measured in kg PM (particulate matter) $_{2.5}$ equivalent.
- Ozone depletion: The depletion of the stratospheric ozone allows larger fraction of harmful UV penetrate earth's surface and can cause harmful effect on human health, animal health, terrestrial and aquatic systems, biochemical cycles and materials. The ozone depletion potential of different gases is expressed as kg CFC-11 equivalent.
- Photochemical smog: The photooxidants are secondary pollutants formed in the lower atmosphere from NO_x and hydrocarbons in presence of sunlight. These substances are characterised as photochemical smog and are expressed as g NO_x equivalent.

The commonly used impact categories, with their classification and characterization factors are listed in Table 3.6.

Table 3.6.Commonly used impact categories with their classification and characterization factors (EPA, 2006)

Impact Category	Scale	Examples of LCI Data (i.e. classification)	Description of Characterization Factor
Global Warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydro chlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Converts LCI data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.
Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydro chlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH3Br)	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Converts LCI data to hydrogen (H+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Converts LCI data to phosphate (PO_4) equivalents.
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)	Converts LCI data to ethane (C_2H_6) equivalents.
Ecotoxicity	Local	Toxic chemicals with a reported lethal concentration to rodents and fish	Converts LC50 data to equivalents; uses multi-media modeling, exposure pathways.
Human Health	Global Regional Local	Total releases to air, water, and soil.	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.

3.5 Sensitivity analysis

Sensitivity analysis is a data quality analysis technique. Sensitivity analysis was undertaken by varying one input variable from the base case scenario while keeping the other variables constant. It measures the extent that changes the LCI results and characterization models affect the impact indicators results (EPA, 2006). It helps to better understand the magnitude of the effect of the assumptions made in the life cycle analysis study. In this study, switchgrass biomass yield and nitrogen fertilizer rates were considered for sensitivity analysis. In Ontario, switchgrass yield has been reported in the range of 8-12 t ha^{-1} (Samson, 2007). Therefore, sensitivity analysis was conducted for high yield (12 t ha^{-1}) and low yield (8 t ha^{-1}) and compared to the base case scenario of average yield (10 t ha^{-1}).

Another sensitivity analysis with different rates of nitrogen fertilizer was undertaken to see the environmental impact associated with high (100 kg N ha^{-1}) and low N application rates (45 kg N ha^{-1}). In a field trial at Don Nott farm it was observed that with lower rate of nitrogen (45 kg N ha^{-1}) there was no difference in the yield from that of 55 kg N ha^{-1} (base case scenario). However, field trials at upper southeastern USA (1999–2000) showed that with increase of nitrogen rate (100 kg N ha^{-1}) yield of switchgrass biomass increases to 14 t ha^{-1} with two cut per year (Fike et al., 2006). Nitrogen fertilization between 56 and 112 kg N ha^{-1} was found to be ideal in terms of fertilizer use efficiency (Lemus et al., 2008). Switchgrass fertility research sponsored by Oak Ridge National Lab (ORNL) over ten years found that stands receiving high nitrogen (N) fertilization levels (101 kg N ha^{-1}) and harvested once in the fall tended to thin out over time (Fike et al., 2006; Parrish et al., 1996). Increased lodging, decreased tiller density, and reduced stand vigor were also observed for these stands. Based on these results, the authors hypothesize that high N rates may maximize short-term yields but reduce long-term yield potential and recommend that N fertilizers be used at limited rates to ensure long-term stand survival. Based on these observations, two fertilizer rate extremes (45 kg N ha^{-1} and 100 kg N ha^{-1}) were selected for sensitivity analysis in this study.

3.6 LCA software

The SimaPro 7.3.2 (System for integrated environmental assessment of products) software developed by PRé Consultants (Products Ecology Consultants) was used for LCA modelling and analysis. The software is well known globally (used in 80 countries) as a professional tool to collect, analyze and monitor the environmental performance of products and services following the ISO 14040 series standards. It is a proven, reliable and flexible tool used by major industries, consultancies and universities and the most successful LCA software worldwide (http://www.earthshift.com/software/simapro). The SimaPro software comes with several databases (libraries) which includes life cycle inventory database and impact methods. One of the databases is ecoinvent developed by Swiss Institute (http://www.pre.nl/content/manuals) that contains about 4100 datasets of products and services from various sectors including agriculture sector. For this present study, ecoinvent unit processes, US-EI, USLCI (US Life Cycle Inventory) databases and methods were used for modelling.

CHAPTER 4

RESULTS

This chapter presents the results of energy use and environmental impact assessment for switchgrass biomass production in Ontario using two harvesting methods. The results are presented in three main categories namely,

- Energy use in production of 1 t switchgrass biomass (Section 4.1)
- Environmental impact of life cycle processes for 1 t switchgrass biomass production under nine impact categories (Section 4.2)
- Sensitivity analysis (section 4.3)

4.1 Energy use of switchgrass biomass production system

The total energy consumption for the production of 1 t switchgrass biomass was 1367 MJ for HS1 and 1697 MJ for HS2 (Table 4.1). The higher energy consumption in the HS2 is primarily due to additional processes (baling) over HS1.

Among all energy sources used in two harvest systems, non- renewable fossil energy constituted about 98% of the total energy consumption.

Table 4.1. Cumulative energy use (MJ) of switchgrass production systems

Energy Source	**Harvest system 1**	**Harvest system 2**
Non-renewable, fossil	1345	1649
Non-renewable, nuclear	17	37
Renewable	5	11
Total energy	**1367**	**1697**

The cumulatuve energy consumed in various life cycle processes of 1 t switchgrass production is presented in Table 4.2. Fertilizer related processes used highest energy (800 MJ) followed by chopping (478 MJ) and baling (324 MJ).

For HS1 (Figure 4.1), fertilizer related processes accounted for 59% of the total energy, followed by 35% for chopping. The rest of the processes accounted for only 7% of the total energy.

On the other hand, in HS2 (Figure 4.2), fertilizer and chopping accounted for 47% and 28% of the total energy, respectively. Baling used 19% of the total energy leaving 6% for the rest of the processes.

Table 4.2. Cumulative energy use (MJ) in different processes

Process	**Energy use (MJ)**	**% of total energy**	
		HS1	HS2
Land preparation	9	1	1
Seed Sowing	6	*	*
Mowing	23	2	1
Herbicide related	14	1	1
Fertiliser related	800	59	47
Swathing	11	1	1
Raking	20	1	1
Chopping	478	35	28
Forage wagon loading (HS1)	6	*	*
Bale Loading (HS2)	12	NA	1
Bailing (HS2)	324	NA	19
Total energy use for HS1	1367	100	NA
Total energy use for HS2	1697	NA	100

**Value less than 1%*

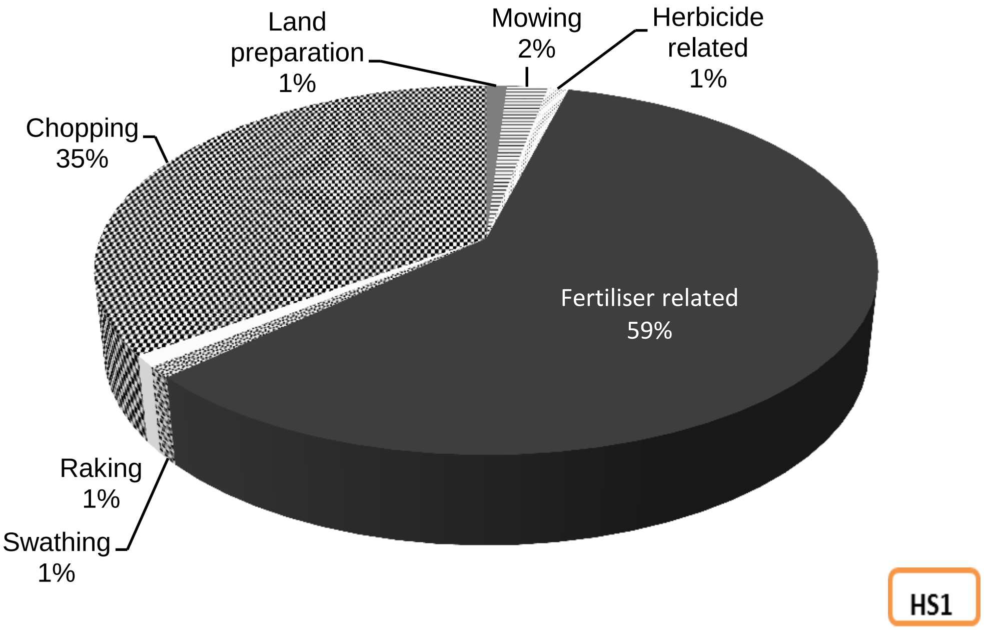

Figure 4.1. Cumulative energy use (MJ) in life cycle processes for HS1

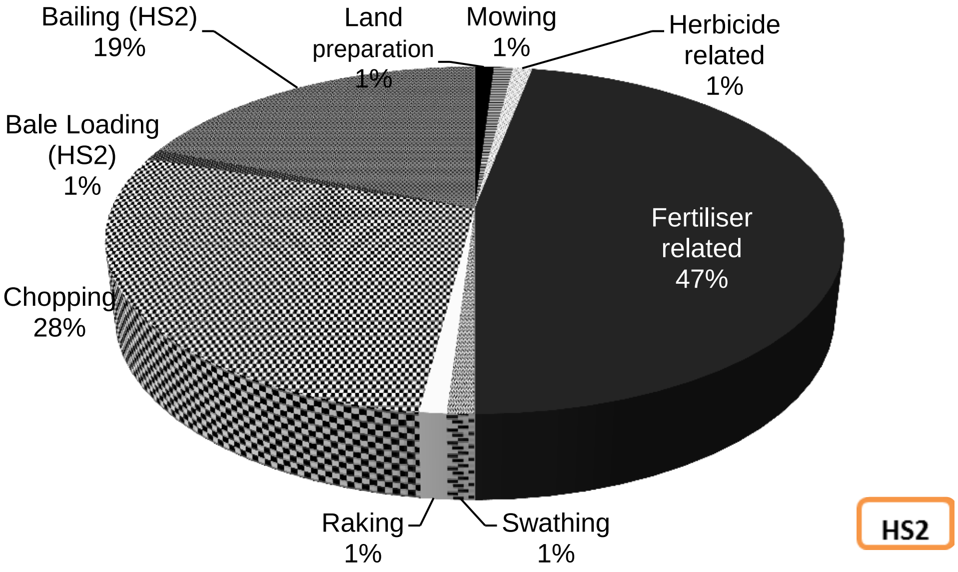

Figure 4. 2. Cumulative energy use (MJ) in life cycle processes for HS2

4.2 Environmental impact of various life cycle processes in switchgrass biomass production

The life cycle processes related to the production of swichgrass (1 t over 10 year period as functional unit) caused various environmental impacts that were measured in terms of potential for global warming, acidification, eutrophication, ecotoxicity, human toxicity (carcinogenics, non carcinogenics, and respiratory effects), ozone depletion and smog.

Table 4.3 and Figure 4.3 present the total environmental impacts of switchgrass life cycle under nine different impact categories using the TRACI 2 impact method in SimaPro. All impact categories showed higher environmental impact in HS2 than in HS1. In HS1, production of 1 t switchgrass showed 191 kg CO_2 eq global warming potential, 58 H+ moles eq acidification, 0.10 kg N eq eutrophication, 1.23E-05 kg CFC-11 eq ozone depletion, 8 kg 2,4-D eq ecotoxicity, 0.33 g NOx eq smog, 0.031 kg benzene eq carcinogenics, 190 kg toluene eq non carcinogenics and 0.07 kg $PM_{2.5}$ eq respiratory effects. In HS2, the corresponding results were 204 kg CO_2 eq global warming potential, 64 H+ moles eq acidification, 0.11 kg N eq eutrophication, 1.33E-05 kg CFC-11 eq ozone depletion, 13.8 kg 2,4-D eq ecotoxicity, 0.44 g NOx eq smog, 0.036 kg benzene eq carcinogenics, 214 kg toluene eq non carcinogenics and 0.09 kg $PM_{2.5}$ eq respiratory effects.

Table 4.3. Total impact of life cycle processes on individual impact categories

Impact category	Unit	Total impact **HS1**	Total impact **HS2**
Global warming	*kg CO_2 eq*	191	204
Acidification	*H+ moles eq*	58	64
Carcinogenics	*kg benzene eq*	0.031	0.036
Non carcinogenics	*kg toluene eq*	190	214
Respiratory effects	*kg PM2.5 eq*	0.07	0.09
Eutrophication	*kg N eq*	0.10	0.11
Ozone depletion	*kg CFC-11 eq*	1.23E-05	1.33E-05
Ecotoxicity	*kg 2,4-D eq*	8.20	13.80
Smog	*g NO_x eq*	0.33	0.44

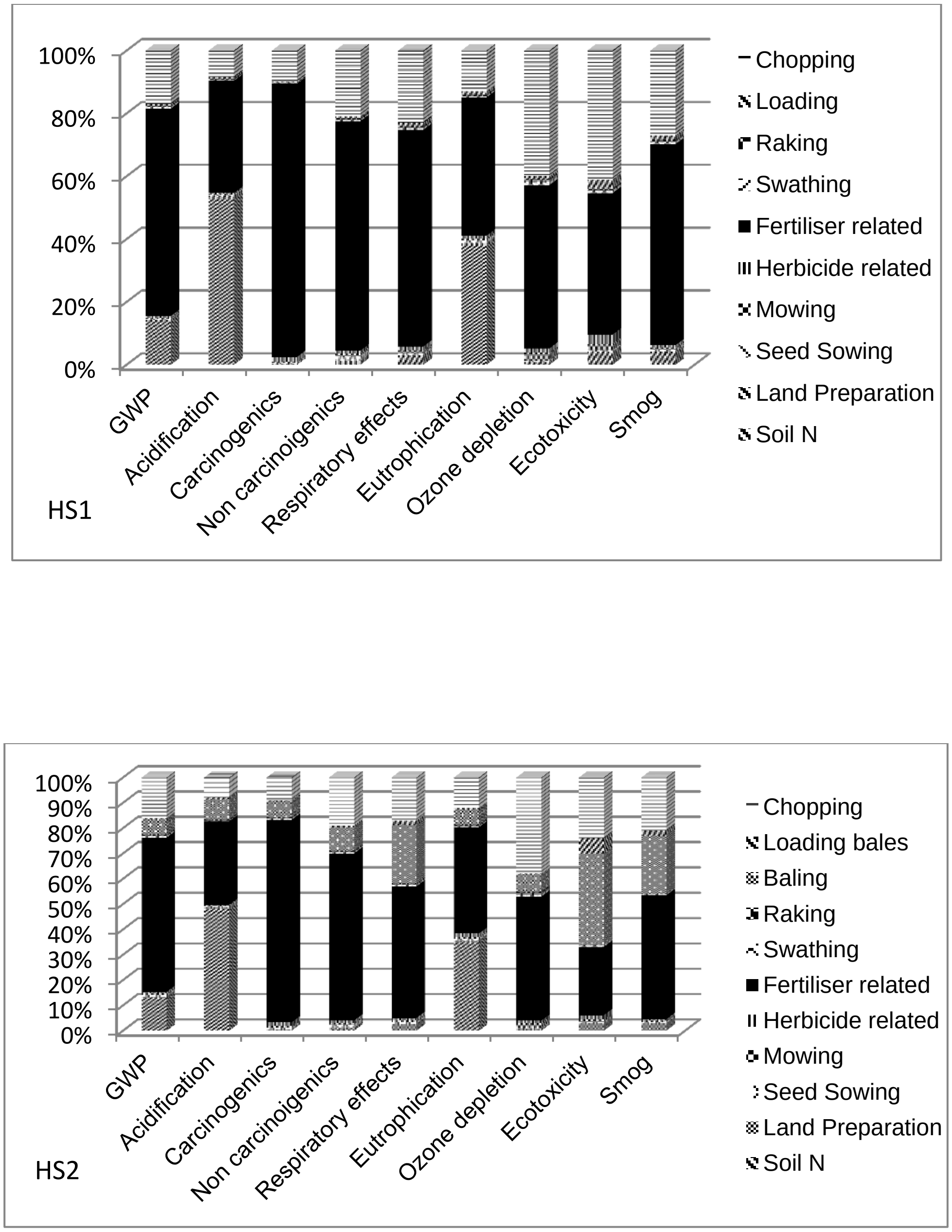

Figure 4.3. Process contribution (%) to each of the nine impact categories (HS1 and HS2)

In HS1 (Figure 4.3), the processes related to fertilization and chopping showed environmental impact across all the impact categories. In HS2, baling process in addition to fertilization and chopping (Figure 4.3) contributed to all the impact categories.

In both HS1 and HS2, fertilizer process contributed more than 50% of the total impacts of five impact categories (carcinogenics, non carcinogenics impact, and respiratory impact, GWP, smog and ozone depletion). Soil nitrogen emission only contributed to GWP, acidification and eutrophication in both HS1 and HS2. The contribution of chopping was the highest towards ozone depletion in HS1 and HS2, whereas baling contributed most to ecotoxicity in HS2. In the following sections, the environmental impact life cycle processes (e.g. land preparation, seed sowing, fertilizer etc.) involved in producing 1 t switchgrass biomass is presented under each of the nine impact categories.

4.2.2 Global warming potential (GWP)

The relative contribution of each of the life cycle processes to the total global warming potential in producing 1 t switchgrass biomass is presented in Figure 4.4 and in the Appendix. The total GWP of HS2 was 204 kg CO_2 eq which was larger than that of the HS1 (191 kg CO_2 eq). The fertilizer related processes contributed most (126 kg CO_2 eq) to the total GWP, followed by chopping (32.46 kg CO_2 eq), soil N emission (27 kg CO_2 eq) and baling (12 kg CO_2 eq). The contribution of the other life cycle processes to the total GWP was very low (less than 1% each).

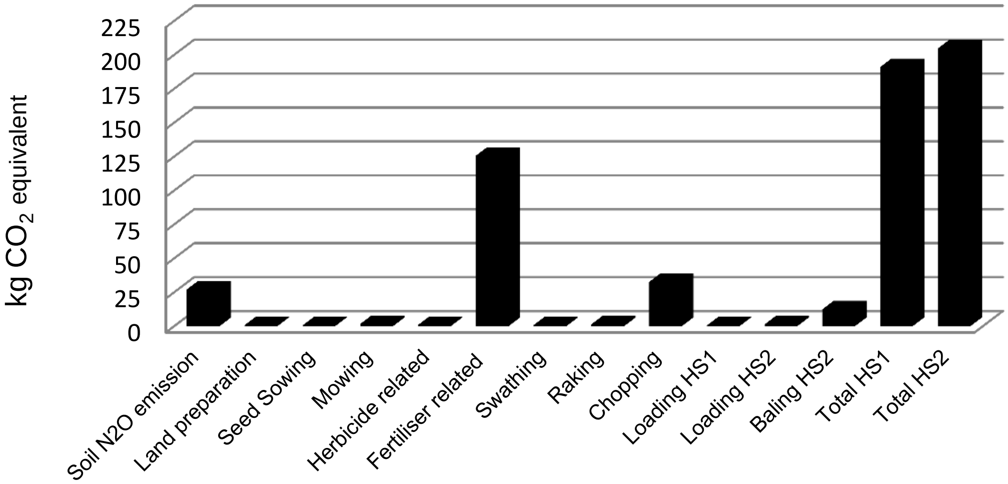

Figure 4.4. Global warming potential of life cycle processes

4.2.3 Eutrophication

The total eutrophication potential of producing 1 t switchgrass biomass was 0.10 kg N eq for HS1, which was slightly lower than that of the HS2 (0.11 kg N eq) (Figure 4.5 and in Appendix). Fertilizer and soil N emission were the two major contributors to the total eutrophication in both HS1 and HS2. The contribution of fertilizer was the highest (0.05 kg N eq) followed by soil N emission (0.04 kg N eq), chopping (0.013 kg N eq) and baling (0.007 kg N eq).

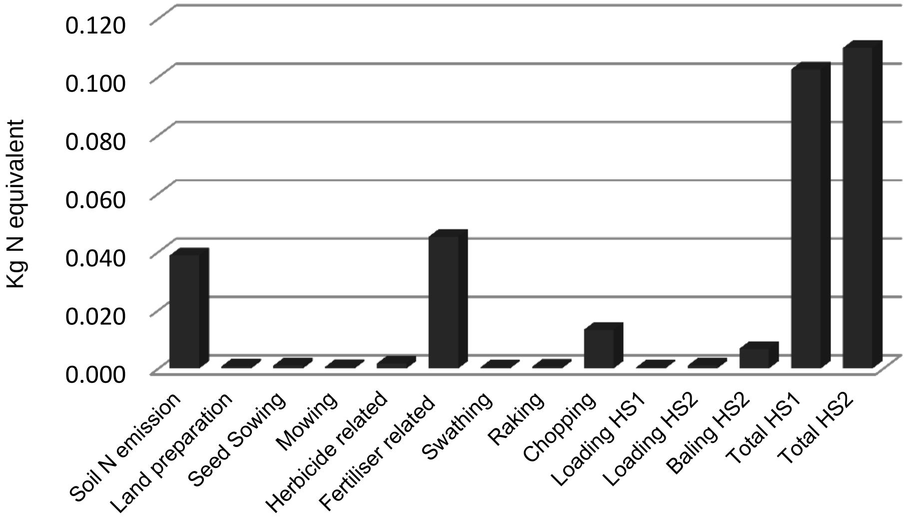

Figure 4.5. Eutrophication potential of life cycle processes

4.2.4 Acidification

The total acidification potential of all the life cycle processes involved in producing 1 t switchgrass was 59 H+ moles eq for HS2 and 65 H+ moles eq for HS1. Among the processes, fertilizer processes and soil nitrogen emission together contributed 81% of the total acidification (Figure 4.6 and in Appendix); however individual contribution of soil N emission was higher (31 H+ moles eq) than that of the fertilizer process (21 H+ moles eq). The contribution of chopping and baling were below 10% each, whereas the rest of the processes had negligible impacts on acidification.

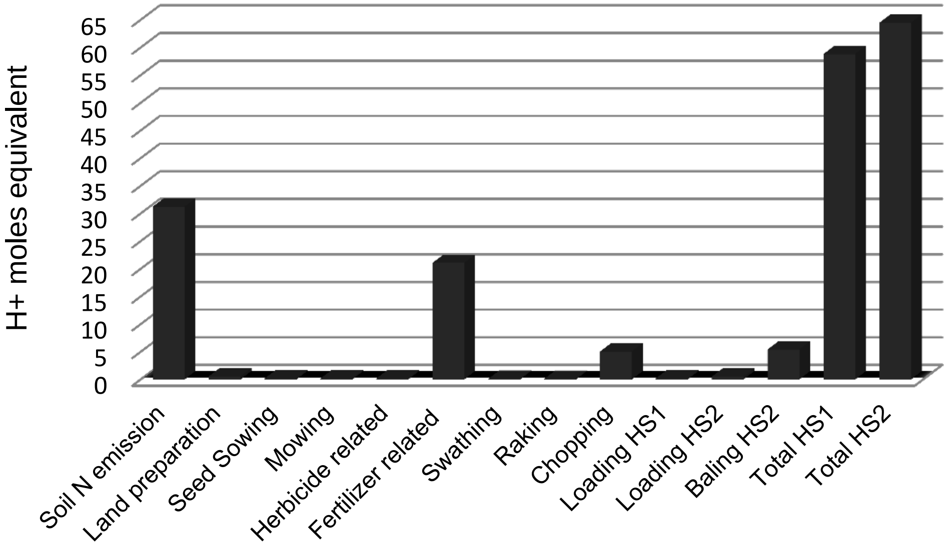

Figure 4.6. Acidification potential of life cycle processes

4.2.5 Toxicity (ecotoxicity, respiratory effects, carcinogenics and non-carcinogenics)

The total ecotoxicity potential (kg 2,4-D eq) of all the life cycle processes involved in producing 1 t switchgrass was 8 for HS1 and 14 for HS2 (Figure 4.7 and Table 4.7 in Appendix). In HS1 and HS2, ecotoxicity potential for fertilizer and chopping were 3.7 and 3.4, respectively). However in HS2, baling contributed 5 kg 2, 4-D eq (36% of the total ecotoxicity).

The total respiratory effect (kg PM $_{2.5}$ eq) of all the life cycle processes involved in producing 1 t switchgrass was 0.07 for HS1 and 0.09 for HS2 (Figure 4.8 and in Table 4.7 in Appendix). Fertilizer processes contributed 0.05 kg PM $_{2.5}$ eq followed by chopping (0.017 kg PM $_{2.5}$ eq). Baling contributed 0.02 kg PM $_{2.5}$ eq (23% of the respiratory effect of HS2).

The total carcinogenic impact (kg benzene eq) of all the life cycle processes involved in producing 1 t switchgrass was 0.03 for both HS1 and HS2 (Figure 4.9 and Table 4.7 in Appendix) where fertilizer related processes contributed up to 87% of the total carcinogenic impact. Chopping and baling contributed below 10% each.

The total non-carcinogenic impact (kg toluene eq) of all the life cycle processes involved in producing 1 t switchgrass was 190 for HS1 and 214 for HS2 (Figure 4.10 and Table 4.7 in Appendix). Fertilizer related processes contributed 138 kg toluene eq of the total non-carcinogenic impact, followed by chopping (41 kg toluene eq) and baling in HS2 (18 kg toluene eq). Other processes together contributed less than 7% of the total non-carcinogenic effect.

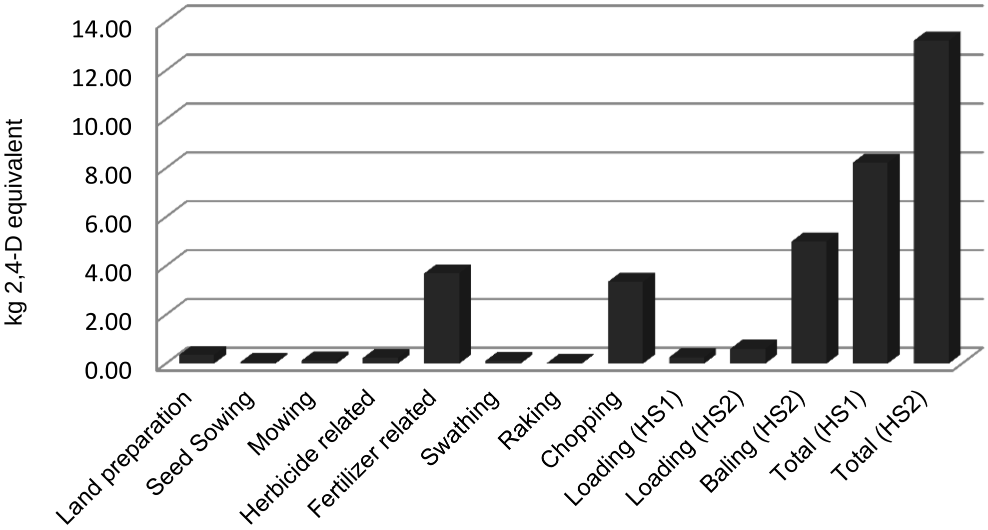

Figure 4.7. Ecotoxicity potential of life cycle processes

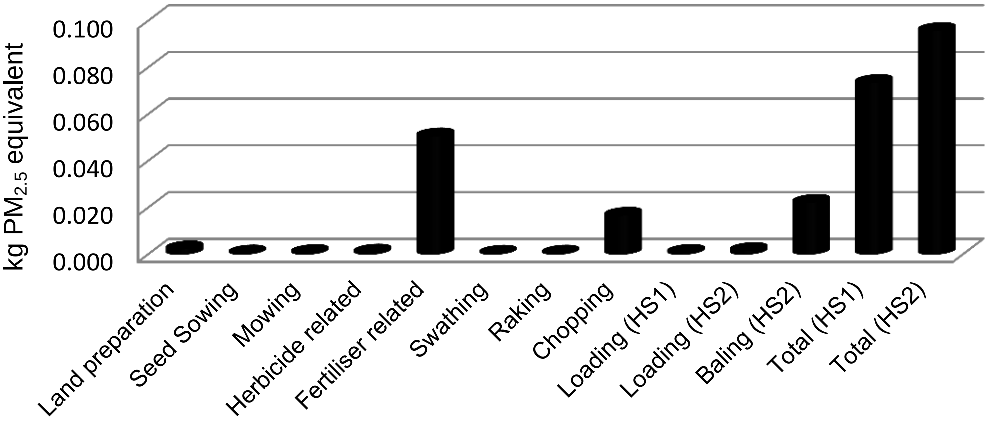

Figure 4.8. Respiratory effect potential life cycle processes

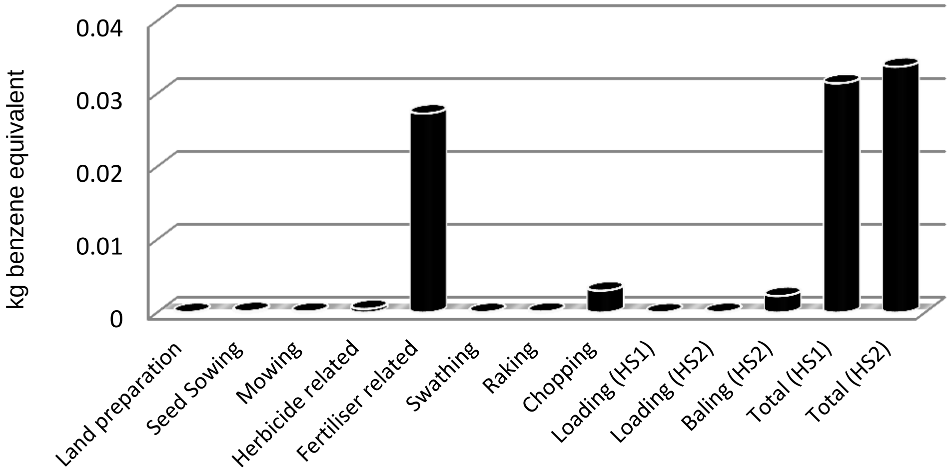

Figure 4.9. Carcinogenics potential of life cycle processes

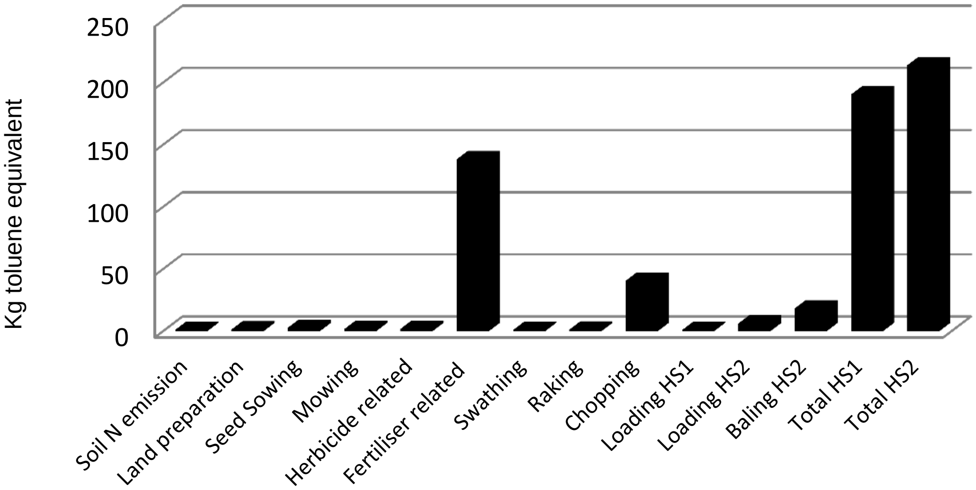

Figure 4.10. Non carcinogenics potential of life cycle processes

4.2.6. Ozone depletion potential

Ozone depletion potential (kg CFC-11 eq) of 1 t switchgrass biomass production was 1.23E-05 for HS1 and 1.32E-05 for HS2. Fertilizer and chopping processes were major contributors. Fertilizer contributed 49% in HS2 and 52% in HS1. On the other hand, chopping contributed 38% in HS2 and 40% in HS1 contribution , respectively to the total ozone depletion potential, depending on the harvest system employed (Figure 4.11 and in Table 4.8 in Appendix).

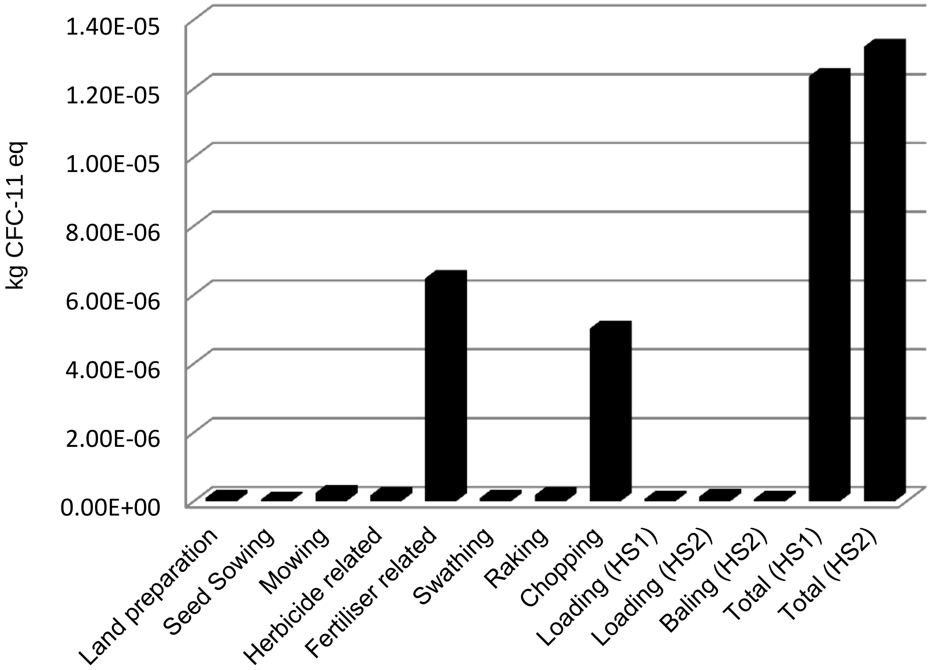

Figure 4.11. Ozone depletion potential of life cycle processes

4.2.7. Smog potential

Like other impact categories, major contributors to smog are fertilizer (49-64%), chopping (21-27%) and baling (23%) depending on harvest system used (Figure 4.12 and Table 4.9 in Appendix).

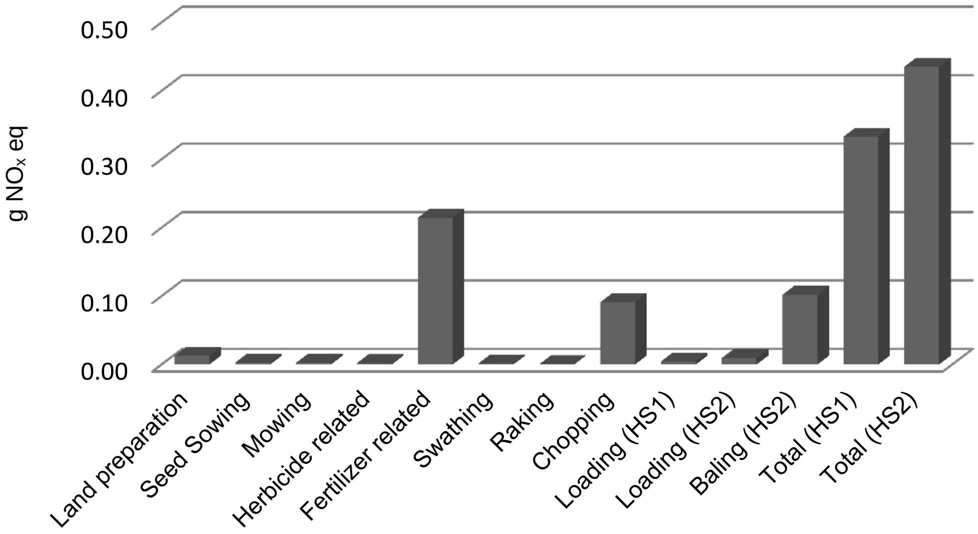

Figure 4.12. Smog potential of life cycle processes

4.3. Sensitivity Analysis

Switchgrass yield and fertilizer dose were considered for the sensitivity analysis using harvest system 2 (HS2).

For this LCA, an average yield of 10 t ha^{-1} was used as a base case scenario to evaluate the impact of various life cycle processes on nine impact factors under two harvesting methods. For sensitivity analysis of this model two alternative yield scenarios were considered to test the sensitivity of this model. In one scenario, low yield of 8 t ha^{-1} was considered and the other scenario considered 12 t ha^{-1} yields. The results of this sensitivity analysis are presented in Table 4.10.

Two other nitrogen fertilizer levels namely, 45 kg N ha^{-1} and 100 kg N ha^{-1} levels, were used to test the sensitivity of LCA model developed using a base case fertilizer rate of 55 kg N ha^{-1} as per recommended for Ontario. The result of the fertilizer sensitivity test is presented in Table 4.11.

From Table 4.10, it is obvious that switchgrass biomass yield is an important parameter that influences all the environmental impact categories considered for this study. With increase in biomass yield from 10 t ha^{-1} to12 t ha^{-1}, carcinogenics, respiratory and ozone depletion showed reductions of approximately 25%. Decreasing yield from 10 t ha^{-1} to 8 t ha^{-1} showed no difference in carcinogenic and respiratory effects, however ozone depletion increased by 12%. Global warming, acidification and non carcinogenics showed 10%, 13% and 12% decline, respectively when yield increased from 10 t ha^{-1} to 12 t ha^{-1}. However, when yield was reduced from 10 t ha^{-1} to 8 tha^{-1}, the impacts increased; 20% in GWP, 23% in acidification and 15% non-carcinogenic. Ecotoxicity showed 7% decrease with 20% increasing biomass yield and 7% increase with 20% yield decline. Smog increased by 25% with 20% decline in biomass yield.

Table 4.10. Difference in environmental impacts with variations of switchgrass yield for HS2

Impact category	Unit	Low yield (8 t ha^{-1})	High annual (12 t ha^{-1})	Average yield (10 t ha^{-1})
Global warming	kg CO_2 eq	245 (+20%)	182 (-10%)	204
Acidification	H+ moles eq	79 (+23%)	56 (-13%)	64
Carcinogenics	kg benzene eq	0.04 (0%)	0.03 (-25%)	0.04
Non carcinogenics	kg toluene eq	247 (+15%)	188 (-12%)	214
Respiratory effects	kg $PM_{2.5}$ eq	0.1 (0%)	0.08 (-25%)	0.1
Eutrophication	kg N eq	0.1 (0%)	0.1 (0%)	0.1
Ozone depletion	kg CFC-11 eq	1.5 E-05 (+12%)	1 E-05 (-24%)	1.33E-05
Ecotoxicity	kg 2,4-D eq	15 (+7%)	13 (-7%)	14
Smog	g NO_x eq	0.5 (+25%)	0.4 (0%)	0.4
The difference of value between high or low yield and average yield were expressed as percentage of value under average yield levels.				

The results of sensitivity analysis with low (45 kg N ha^{-1}) and high (100 kg N ha^{-1}) fertilizer dose are presented in Table 4.11. With 18% reduction of fertilizer N dose (to 45 kg N ha^{-1}) from the base case scenario (55 kg N ha^{-1}), the decrease in impact categories was observed for GWP by 43 %, carcinogenics by 25%, acidification by 14%, non carcinogenics by 13%, ozone depletion by 8% and ecotoxicity by 7%; however no change was observed for respiratory effects, eutrophication and smog was observed. On the other hand 85% increase in fertilizer dose (to 100 kg N ha^{-1}) resulted in 63% increase in GWP, 75% increase in carcinogenics, 69% increase of acidification, 52% increase of non carcinogenics, 54% increase in ozone depletion, 100% increase in eutrophication, 50% increase of smog, 21% increase of ecotoxicity. Only respiratory effects were unaffected by a change in fertilizer dose.

Table 4.11 Difference in environmental impacts with variations of fertilizer doses for HS2

Impact category	Unit	Low fertilizer (45 kg N ha^{-1})	High fertilizer (100 kg N ha^{-1})	Average fertilizer (55 kg N ha^{-1})
Global warming	kg CO_2 eq	117 (-43%)	332 (+63%)	204
Acidification	H+ moles eq	55 (-14%)	108 (+69%)	64
Carcinogenics	kg benzene eq	0.03 (-25%)	0.07 (+75%)	0.04
Non carcinogenics	kg toluene eq	186 (-13%)	326 (+52%)	214
Respiratory effects	kg $PM_{2.5}$ eq	0.1 (0%)	0.1 (0%)	0.1
Eutrophication	kg N eq	0.1 (0%)	0.2 (+100%)	0.1
Ozone depletion	kg CFC-11 eq	1.2 E-05 (-8%)	2 E-05 (+54%)	1.3E-05
Ecotoxicity	kg 2,4-D eq	13 (-7%)	17 (+21%)	14
Smog	g NOx eq	0.4 (0%)	0.6 (+50%)	0.4
The difference of value between high or low fertilizer and average fertilizer were expressed as percentage of value under average fertilizer dose.				

CHAPTER 5

DISCUSSION

Switchgrass has been identified as a promising biomass crop in Ontario for various potential applications including biomaterials and bioenergy. As stated in the previous chapters, there is a lack of comprehensive environmental analysis on switchgrass biomass production in Ontario to estimate the environmental impacts of life cycle processes. In the present study, LCA methodology was used to evaluate energy demand and environmental impacts associated with the production of switchgrass biomass in Ontario. Based on the results obtained, this chapter presents a synthesis and summary of the main findings of the energy analysis, environmental impact assessment, hotspot analysis and the implications of this research.

5.1. Energy analysis

Agricultural production systems are highly mechanized, input intensive and therefore consume high levels of energy. Cumulative energy requirements for producing biomass crops help to explain the energy balance (ratio of input energy and output energy) of biobased products made from biomass crops. The present study indicates that the current switchgrass production practices in Ontario use 1.3-1.7 GJ t^{-1} cumulative energy. Production of agrochemicals (fertilizer and herbicide) and diesel fuel, transportation of inputs and diesel use in harvesting operations were the process contributors to the cumulative energy consumption. Earlier in the US, Kim and Dale (2004) estimated cumulative energy requirements of switchgrass biomass production and transportation to be 0.97-1.34 GJ t^{-1} and compared this with results for corn

(1.99- 2.66 GJ t^{-1}), soybeans (1.98-2.04 GJ t^{-1}) and alfalfa (1.24 GJ t^{-1}). However, the lower energy value (0.97 GJ t^{-1}) was due to allocation of the resources and emissions to the byproducts of N fertilizer production. In that study, nitrogen fertilizer and diesel use were the main contributors to the cumulative energy demand for producing switchgrass.

In the present study, fertilizer related processes, chopping and baling together accounted for 94% of the cumulative energy consumption (Table 4.2) for switchgrass production using either of the two harvesting methods. The rest 6% is contributed by the other processes. Current Ontario switchgrass production considers application of only nitrogen fertilizer. The rate N application to swichgrass is lower (55 kg N ha^{-1} yr^{-1}) than that of typical annual crops such as grain corn (144 kg N ha^{-1}). Ammonium nitrate fertilizer production, transportation and application to the crop accounted for 0.8 GJ cumulative energy which were the major contributors (47-59%) to the total cumulative energy use in switchgrass biomass production. Ninety seven per cent of the 0.8 GJ (774 GJ) came from ammonium nitrate production. In ammonium nitrate production, production of ammonia and nitric acid uses natural gas as major source of energy. The balance 3% of the total energy use in fertilizer related processes was due to fertilizer transport and application to the crop. For conventionally produced crops (not organic agriculture), production of fertilizer was the dominant contributor of cumulative energy demand (Pelletier et al., 2008). The cumulative energy analysis of the present study confirmed that fertilizer production and harvesting operations (chopping and baling) were major processes impacting cumulative energy use in switchgrass biomass production. Similar result was confirmed by other studies for a range of cropping systems (Gallego et al., 2011; Kim et al., 2009; Monti et al., 2009). A recent study on hemp and flax reported significant contributions of nitrogen fertilizer to total energy consumption (González-García et al., 2010). Switchgrass biomass production with HS1 was more energy efficient than HS2, because the energy intensive (0.3 GJ t^{-1}) baling process is not used in HS1. Chopping of switchgrass used about 0.5 GJ t^{-1} of the cumulative energy and 83% of this energy was contributed by diesel fuel production used by chopping machinery; the remaining 17% was for transportation of diesel fuel. Baling (in harvest system 2) accounted for 19% of the cumulative energy used in switchgrass biomass production where 77% of this energy comes from polythene production and 23% from production of diesel fuel used in baling machinery.

Previous studies in Canada (Girouard et al., 2005) showed that 51.5 % of the total energy in switchgrass production was attributed to fertilizer. The cradle-to-farm gate life cycle data for the cumulative energy demand in producing several other annual crops was 5.2 GJ t^{-1} for canola, 2.4 GJ t^{-1} for corn, 2.3 GJ t^{-1} for soybeans and 2.7 GJ t^{-1} for wheat (Pelletier et al., 2008). In the same study, the production of fertilizer was dominant contributor (average 62% for all crops) to cumulative energy demand for producing these crops. The energy cost of manufacturing inorganic fertilizer, particularly nitrogen fertilizer is high due to extremely high energy intensive Haber-Bosch process of fertilizer manufacturing that requires large input of natural gas (Samson et al., 2005).

The net energy ratio (biomass energy content at the farm gate divided by the fossil energy consumed in production) indicates energy performance of a production system. The input (fossil energy required to produce 1 t switchgrass) to output energy (18.5 GJ t^{-1} energy content of switchgrass) ratio for switchgrass in our present study ranged from 11 (HS2) to 14 (HS1) which was found to be14.6 in the previous study (Samson et al., 2005).

It was reported that net energy balance may vary depending on crop yield, fertilizer manufacturing efficiency and application rate (Shapouri et al., 1995, 2002). From cumulative energy demand perspective, HS1 is more energy efficient than HS2.

The results of other studies discussed here give a relative idea of cumulative energy demand by switchgrass and other crops, but those results cannot be compared directly with the present study due to the differences in the life cycle processes considered, allocation of energy and types of crops. Improvement of switchgrass yield, standardization of harvesting operations to reduce energy use is important considerations for reducing cumulative energy demand in switchgrass biomass production.

5.2 Environmental impact assessment

In addition to cumulative energy use, the present study considered nine different impact categories and soil nitrogen (NH_3 and N_2O) emissions to assess the environmental impacts of switchgrass biomass production. This is important in order to understand the potential impacts of growing switchgrass on soil, air, water and biodiversity.

The present study showed that the processes related to fertilizer, harvesting (chopping and baling) and soil nitrogen emissions contributed to most of the impact categories in switchgrass biomass production.

Global warming potential, which is responsible for climate change, is defined as the impact of emissions on the heat radiation absorption of the atmosphere. Emissions such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O) are mostly responsible for an anomalous warming of the earth surface. Growing switchgrass in Ontario with current practices resulted in total global warming potential in the range of 190-204 CO_2 eq t^{-1} switchgrass biomass. Among all the processes, fertilizer (nitrogen) related process contributed the largest (61-66%) portion of the total global warming potential followed by the chopping (16-17%), soil nitrogen emission (14%) and baling (6%). However, the remaining eight processes contributed less than 1% each to the total global warming potential (Table 4.4). The greenhouse gases released from ammonium nitrate production, soil emission and diesel fuel combustion for machinery were the primary sources of global warming impact from switchgrass biomass production. Nitrous oxide contributed the most to the total global warming potential followed by carbon dioxide.

Earlier studies in Europe and U.S. (Kim and Dale, 2004; Monti et al., 2009; Adler et al., 2007) estimated the global warming potentials of growing switchgrass. The global warming impact associated with producing biomass is 246 to 286 kg

CO_2 eq t^{-1} for corn, 159 to 163 kg CO_2 eq t^{-1} for soybeans, 89 kg CO_2 eq t^{-1} for alfalfa, and 124 to 147 kg CO_2 eq t^{-1} for switchgrass (Kim and Dale, 2004). However, it is difficult to compare GWP data of the present study with that of the published data due to differences in system boundary, fertilizer rates and types, emission factors, allocation and the processes considered. The results of the present study confirmed that fertilizer and harvesting processes are two major sources of greenhouse gas emissions leading to global warming. The same two processes also accounted for a major (94%) share of the cumulative energy consumption. Other studies also revealed that N-fertilization affected acidification, GWP, ozone layer depletion and toxicity (Gallego et al., 2011; Monti et al., 2009).

Soil carbon sequestration is another benefit from growing crops including switchgrass. It was estimated that the credit for soil carbon dioxide sequestration was 180 g CO_2 kg^{-1} switchgrass (Qin et al., 2006). Therefore soil carbon sequestration will result in an overall reduction of atmospheric carbon dioxide and therefore global warming caused by crop production. Considering 180 kg t^{-1} carbon dioxide sequestration, the net GWP caused by switchgrass biomass production in the present study was found to be considerably low (11-24 kg CO_2 t^{-1}).

The use of agro-chemicals is another important source of emissions from a crop production system contributing significantly to global warming, acidification and eutrophication (Charles et al., 2006). The present study showed that fertilizer (44%) and soil emission (35-38%), under the present switchgrass cultivation scenario, contributed significantly to the eutrophication. Although nitrogen and phosphorus are two nutrients most associated with eutrophication, eutrophication potential in the present study was primarily linked to nitrogen (only ammonium nitrate fertilizer was used to grow switchgrass). The improvement in N fertilization leading to reduction of nitrogen emissions ($N_{2,}$ NH_3, and N_2O) to air reduced eutrophication impact (Gallego et al., 2011).

Acidification, smog, ozone depletion and toxicity (ecotoxicity, respiratory effects, carcinogenics and non carcinogenics) were impacted mainly by fertilization and chopping processes. N fertilizer use leads to different emissions (N_2O, NH_3, NOx and NO_3) which contributed considerably to eutrophication, acidification and GWP (González-García et al., 2010). Diesel production and combustion in the other processes (chopping and bailing) is likely to be associated with eutrophication which was also reported for wheat, hemp and sugar beet production processes (van der Werf, 2004).

In the present study, soil N emission contributed significantly to acidification (about 48%), eutrophication (35%) and global warming potential (about 14%). However, it did not impact noticeably on other impact categories. Some of the unused (by crop) nitrogenous fertilizers and manure applied to crop results in nitrous oxide emissions (also as N_2) from soil to the atmosphere and as nitrogen leaching or run off from the soil to surface or ground water sources.

5.3 Identification of hot spots

Hot spot refers to the processes that are responsible for the highest contribution to the environmental impact categories and energy use. In this study, hot spot was identified as the element or process that had more than 10% contribution to a single impact category (Gallego et al., 2011). From this present study, fertilizer related process, soil N emission and chopping in switchgrass production were identified as emission and energy use hot spots (Table 5.1). For the system studied, the major three hot spots made up more than 95% to GWP, eutrophication and acidification impacts. However, for the other impact categories, fertilizer and chopping were key hot spots being responsible for more than 85% of the impacts.

Table 5.1. Percent contribution of switchgrass life cycle processes to different impact categories

Impact category	**Fertiliser related**	**Chopping**	**Soil N emission**	**Baling (in HS2)**
GWP	61-66	16-17	13-14	Less than 10
Eutrophication	41-44	12-13	35-38	Less than 10
Acidification	33-36	Less than 10	48-53	Less than 10
Ozone depletion	49-52	38-40	Nil	Less than 10
Smog	49-64	21-27	Nil	23
Ecotoxicity	27-45	24-41	Nil	36
Respiratory effects	53-69	18-23	Nil	23
Carcinogenics	81-87	9-10	Nil	Less than 10
Non carcinogenics	65-73	19-21	Less than 1%	Less than 10

5.4. Conclusion and future direction of research

The present study generated base line LCA data for the environmental impacts of growing switchgrass in Ontario. Through the hot spots analysis, fertilizer and harvesting operations and soil nitrogen emission were identified as the key processes contributing to the environmental impact of switchgrass biomass production. This opened up several new research streams that might be targeted to reduce environmental footprint of switchgrass biomass production system through:

- Efforts to increase the yield potential of switchgrass (by genetic improvement, region specific varietal selection) with less input requirement. The nitrogen content of the harvested biomass is an important parameter to reduce the fertilizer requirement of the plant. For example, increasing the stem to leaf ratio of switchgrass can reduce the nitrogen requirement (Samson, 2005).
- A detail study on the optimum rate and type of nitrogen fertilizer would be helpful to reduce the emission in most of the impact categories. It was reported that some temperate switchgrass ecotypes (blue green) utilizes biological nitrogen fixation. Therefore, varietal screening and development of new cultivars with biological nitrogen fixation potential would be important.
- Dataset generated in this research can be used to evaluate the environmental performance of switchgrass based bioproducts.
- A comparative LCA study of switchgrass with other biomass crops will help to understand the relative environmental performance.

REFERENCES

Abramson, M., Shoseyov, O., and Shani, Z. 2010. Plant cell wall reconstruction toward improved lignocellulosic production and process ability. Plant Science, 178:61–72.

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

Bai, Y., Luo, L., and Voet, E.V. 2010. Life cycle assessment of switchgrass-derived ethanol as transport fuel. Int. J of Life Cycle Assess, 15: 468-477.

Bare, J.C., Norris, G.A., Pennington, D.W., and McKane, T. 2002. TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. Journal of Industrial Ecology, 6:49-78.
Available at http://mitpress.mit.edu/journals/pdf/jiec_6_3_49_0.pdf

Bare, J., Gloria T., and Norris, G. 2006. Development of the Method and U.S. Normalization Database for Life Cycle Impact Assessment and Sustainability Metrics. Environ. Sci. Technol, 40:5108-5115.

Baumann, H., and Tillman, A. 2004. The Hitch Hikers Guide to LCA: An orientation in life cycle assessment methodology and application. Published by Studentlitteratur AB, Lund, Sweden.

Bernstad, A. K., Cour Jansen, J. la., and Aspegren, H. 2011. Life cycle assessment of a household solid waste source separation programme: a Swedish case study. Waste management & research: the journal of the International Solid Wastes and Public Cleansing Association, ISWA, (6).

Bhattacharyya, D. and Jayaraman, K. 2003. Manufacturing and evaluation of wood fibre-waste plastics composite sheets. Polymers and Polymer Composites, 11:433-440.

Biswas, W. K., Barton, L., and Carter, D. 2008. Global warming potential of wheat production in Western Australia: a life cycle assessment. Water and Environment Journal, 22: 206–216.

Blengini, G.A. and Busto, M. 2009. The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy). Journal of Environment Management, 90:1512–22.

Brander, M.1, Tipper, R.1, Hutchison, C.1, and Davis, G. 2008. Technical Paper Consequential and Attributional Approaches to LCA: a Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels. Ecometrica press. Available at http://www.globalbioenergy.org/uploads/media/0804_Ecometrica_-Consequential_and_attributional_approaches_to_LCA.pdf

Burras, L. and McLaughlin, J. 2002. Soil organic carbon in the fields of switchgrass and row crops as well as woodlots and pasture across the Chariton Valley, Iowa. Final Report, Cooperative agreement between Chariton valley resource conservation and development, INC. and Iowa state university. Available at http://www.iowaswitchgrass.com/__docs/pdf/SOC%20Final%20Report.pdf

Carpenter, S., Caraco, N. and Correl, D.1998. Non-point pollution of surface waters with phosphorus and nitrogen. Ecological Applications, 8:559–568.

Carvalho, F. P. 2006. Agriculture, pesticides, food security and food safety. Environmental Science and Policy, 9:685–692.

Charles R, Jolliet O, Gaillard G, Pellet D. 2006. Environmental analysis of intensity level in wheat crop production using life cycle assessment. Agr Ecosyst Environ, 113:216–25.

Cherubini, F., and Jungmeier, G. 2009. LCA of a biorefinery concept producing bioethanol, bioenergy, and chemicals from switchgrass. The International Journal of Life Cycle Assessment, 15:53-66.

Clair, S., Hillier, J. and Smith, P. 2008. Estimating the pre-harvest greenhouse gas costs of energy crop production. Biomass and Bioenergy, 32:442-452.

Dukes, J. S. 2003. Burning buried sunshine: Human consumption of ancient solar energy. Climatic Change, 61:31–44.

Dunn, D.P., Stearns, F., Guntenspergen, G.R., and Sharpe, D.M. 1993. Ecological benefits of the Conservation Reserve Program.Conservation Biology, 7:132–139.

Elbersen, H.W., Christian, D.G., Bassem N. E, Bacher W., Sauerbeck G., Alexopoulou, E., Sharma, N., Piscioneri, I., Vissern, P. de., and van den Berg, D. 2001. Switchgrass (Panicum virgatum L.) as an alternative energy crop in Europe -Initiation of a productivity network. Final report FAIR. Available at http://www.switchgrass.nl/pdf/Sw_FinalRep_full2.pdf

Environment Canada, 2009. National Inventory Report: Greenhouse gas sources and sinks in Canada, 1990-2009. Available at http://www.ec.gc.ca/ges-ghg/default.asp

Environmental Protection Agency (EPA). 2006. Life Cycle Assessment: Principle and Practices. Available at http://www.epa.gov/ORD/NRMRL/lcaccess/pdfs

Eucar-JRC-Concawe, 2007. Well to wheel analysis of future automotive fuels and powertrains in the European context. Available at http://ies.jrc.ec.europa.eu/uploads/media/TTW_App_1_010307.pdf

Fike, J. H., Parrisha, D.J., Wolfa, D.D., Balaskob, J.A., Green Jrc, J.T., Rasnaked, M., and Reynoldse, J.H. 2006. Long-term yield potential of switchgrass-for-biofuel systems. Biomass and Bioenergy, 30:198–206.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., and Suh, S. 2009. Recent developments in life cycle assessment. Journal of Environmental Management, 91:1-21.

Follett, R.F., Pruessner, E.G., Samson-Liebig, S.E., Kimble, J.M. and Waltman, S.W. 2001. Carbon sequestration under the CRP in the historic grassland soils in the USA. In: Lal, R. (ed) Soil carbon sequestration and the greenhouse effect. SSSA. Madison, WI. 27-44.

Fox, G., Girouard, P., and Syaukat, Y. 1999. An economic analysis of the financial viability of switchgrass as a raw material for pulp production in eastern Ontario. Biomass and Bioenergy, 16: 1-12.

Frankl, P. and Rubik, F. (eds). 2000. Life cycle assessment in industry and business. Adoption patterns, applications and implications. Springer Verlag, Berlin, Germany.

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.

Frischknecht, R., and Jungbluth, N. 2003. Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000, Swiss Centre for LCI. Dübendorf, Switzerland. Available at http://www.ecoinvent.org/

Frischknecht, R., Jungbluth, N., Althaus, H.J., Doka, G., Dones, R., Hischier, R., Hellweg, S., Humbert, S., Margni, M., Nemecek, T., and Spielmann, M. 2007.

Implementation of Life Cycle Impact Assessment Methods: Data v2.0. ecoinvent report No. 3, Swiss centre for Life Cycle Inventories, Dübendorf, Switzerland.

Gallego, A., Hospido, A., Moreira, M T. and Feijoo, G. 2011. Environmental assessment of dehydrated alfalfa production in Spain. Resources, Conservation and Recycling. 55: 1005-1012.

Gasol, C.M. 2007. Life cycle assessment of *Brassica carinata* bioenergy cropping system in southern Europe. Biomass Bioenergy, 8: 543-555.

Gerhardt, R. 1997. A comparative analysis of the effects of organic and conventional farming systems on soil structure. Biological Agriculture and Horticulture, 14:139–157.

Girouard, P., Henning, J.C., and Samson, R. 1996. Economic assessment of short-rotation forestry and switchgrass plantation for energy production in central Canada. Proceedings of the Canadian energy plantation workshop, Natural Resource Canada. 21-26.
Available at http://www.reap-canada.com/online_library/agri_fibres_forestry/

Girouard, P., Zan, C., Mehdi, B., and Samson, R. 1999. Economics and carbon offset potential of biomass fuels. Final Report by REAP Canada to PERD programme, Natural Resource Canada.
Available at http://www.reap-canada.com/online_library/ghg_offsets_policy/

Girouard, P., Mehdi, B., Samson, R., and Blais, P. A. 1999. Commercial production of switchgrass in Ontario; A management Guide. REAP Canada, Qubec.
Available at http://www.reap-canada.com/online_library/Reports

González-García, S., Hospido, A., Feijoo, G., and Moreira M.T. 2010. Life cycle assessment of raw materials for non-wood pulp mills: Hemp and flax. Resources, Conservation and Recycling. Article in press. Available at http://193.146.160.29/gtb/sod/usu/$UBUG/repositorio/10300582_Gonzalez.pdf

Graboski, M. S. 2002. Fossil Energy Use in the Manufacture of Corn Ethanol. Prepared for National Corn Grower Association, U.S.
Available at
http://www.oregon.gov/ENERGY/RENEW/Biomass/docs/FORUM/FossilEnergyU

Hautala, M., Parsila, A., and Pirilä , J. 2004. Use of hemp and flax in composite manufacture: a search for new production methods. Compos Part A: Applied Sci, 35:11-16.

Heiskanen, E. 2000. Translation of an environmental technique: Institutionalization of the life cycle approach in business, policy and research netwaorks. A-178, Acta Universitatis Oeconomicae Helsingiensis. Helsinki School of Economics and Business Administration.

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

Hetrick, B. A. D., Wilson, G. W. T., and Leslie, J. 1991. Root architecture of warm- and cool-season grasses: relationship to mycorrhizal dependence. Can. J. Biol, 69: 112–118.

Hohenstein, W.G., and Wright, L.L. 1994. Biomass energy-production in the United States – an overview. Biomass and Bioenergy, 6: 161–173.

Hultquist, S.J., Vogel, K.P., Lee, D.J., Arumuganathan, K., and Kaeppler, S. 1996. Chloroplast DNA and nuclear DNA content variations among cultivars of switchgrass, *Panicum virgatum* L. Crop Sci. 36: 1049- 1052.

Industry Canada. 2010. Technology Road maps: Innovation Roadmap on Bio-based Feedstocks, Fuels and Industrial Products — Biomass Availability Technology Roadmaps. Available at http://www.ic.gc.ca/eic/site/trm-crt.nsf/eng/rm00118.html

Intergovernmental Panel for Climate Change. 2007. The Physical Science Basis. Cambridge University Press, Cambridge. Available at http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_

Intergovernmental Panel for Climate Change. 2011. Special IPCC Report on Renewable Energy Sources and Climate Change Mitigation. IPCC, Geneva.

ISO, 2006a ISO 14040 International Standards. In: Environmental Management – Life Cycle Assessment – Principles and Framework. International Organisation for Standardization, Geneva, Switzerland.

ISO, 2006b ISO 14044 International Standards. In: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organisation for Standardisation, Geneva, Switzerland.

Jannasch, R., Samson, R., Maio, A. De., Adams, T., and Lem, C. Ho. 2001. Resource Efficient Agricultural Production Canada and Energy Probe presentation at “Climate Change 2: Canadian Technology Development Conference”. Canadian Nuclear Society, Toronto, Oct 3-5. Available at http://www.reapcanada.com/online_library/ghg_offsets_policy

Jannasch, R., Duxbury, P., and Samson, R. 2001. Development of Bioenergy Feedstocks: Agronomy Data from Eastern Canada Final Report. Resource Efficient Agricultural Production (REAP) – Canada. Available at http://www.reap-anada.com/online_library/feedstock_biomass

Janzen, H.H. 2004. Carbon cycling in earth systems - a soil science perspective. Agriculture, Ecosystems and Environment, 104: 399–417.

Jefferson, P. G., McCaughey, W. P., May, K., Woosaree, J., McFarlane, L., and Wright, S. M. B. 2002. Performance of American native grass cultivars in the Canadian prairie provinces. Native Plants J. 3: 24–33.

Kaltschmitt,M., Reinhardt, G., and Stelzer, T. 1997. Life cycle analysis of biofuels under different environmental aspects. Biomass and Bioenergy. 2: 121-134.

Keshwani, D. R., and Cheng J. J. 2009. Switchgrass for Bioethanol and Other Value-Added Applications: A Review. Bioresource Technology, 100: 1515–1523.

Kim, S., and Dale, B.E. 2004. Cumulative Energy and Global Warming Impact from the Production of Biomass for Biobased Products. J of Industrial ecology, 7:147-162.

Kim, S., and Dale, B.E. 2005. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. Biomass and Bioenergy, 29: 426–439.

Kloverpris, J.H., Smith, W., and Bentham, M.J. 2009. Life Cycle Assessment of US Corn Production and Canadian Canola Production with the Yield Enhancing Microbial Phosphate Inoculant JumpStart. A joint report from Novozyme and Agriculture and Agri. Food Canada. Available at http://www.novozymes.com/en/sustainability/sustainable-solutions/life-cycle-assessments/Documents/English.pdf

Knott, D., and Knott, P. 2009. Biomass Heat in Ontario Pioneer's In Making it Happen, Growing the Margins conference, London, Ontario, Canada. Available at http://www.gtmconference.ca/site/index.php/component/

Lee, D.K., Owens, V.N., and Doolittle, J.J. 2007. Switchgrass and soil carbon sequestration response to ammonium nitrate, manure, and harvest frequency on Conservation Reserve Program land. Agron J. 99:462–468.

Lemus, R., and Lal, R. 2005. Bioenergy crops and carbon sequestration. Critical Reviews in Plant Sciences, 24:1-21.

Lemusa, R.,Brummerb,E.C., LeeBurrasc, C., Moorec, K.J., Barkerc, M.F., and Molstad N.E. (2008). Effects ofnitrogen fertilization on biomass yield and quality in large fields of established switchgrass in southern Iowa,USA. Biomass and Bioenergy, 32:1187–1194.

Lewandowski, I. 2003. Delayed harvest of Miscanthus – influences on biomass quantity and quality and environmental impact of energy production. Euro. J. Agron. 19:45-63.

Lewandowski, I., Scurlock, J. M. O., Lindvall, E., and Christou, M. 2003.The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass and Bioenergy. 25:335-361.

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

Liebig, M.A., Schmer M.R., Vogel, K. P., and Mitchell, R. B. 2008. Soil carbon storage by switchgrass grown for bioenergy. Bioenerg. Res. 1: 215-222.

Ma, Z., Wood, C.W., and Bransby, D.I. 1999. Soil management impacts on soil carbon sequestration by switchgrass. Biomass and Bioenergy. 18:469–477.

Madakadze, I. C., Coulmanb, B. E., Mcelroyc, A. R. Stewarta, K. A., and Smitha, D. L. 1998. Evaluation of selected warm season grasses for biomass production in short season area. Bioresource Technology. 65: 1-12.

McDonald, I., Banks, S. 2008. Bio-Energy Crop Research, OMAFRA publication. Available at http://www.omafra.gov.on.ca/english/crops/field/news/croptalk

McLaughlin, S.B. 1993. New switchgrass biofuels research program for the southeast. In: Proceedings 1992 Annual Automative Technology Development, 111–115.

McLaughlin, S.B., Bouton, J., Bransby, D., Conger, B.V., Ocumpaugh, W.R., Parrish, D.J., Taliaferro, C., Vogel, K.P., and Wullschleger, S.D. 1999. Developing switchgrass as a bioenergy crop. In: Janick, J. (Ed.), Perspectives on New Crops and New uses. ASHS Press, Alexandria, VA. 282–299.

McLaughlin, S.B., and Kszos, L.B. 2005. Development of switchgrass(Panicum virgatum) as a bioenergy feedstock in the United States. Biomass and Bioenergy. 28:515-535.

McLaughlin, S., and Walsh, M. 1998. Evaluating environmental consequences of producing herbaceous crops for bioenergy. Biomass and Bioenergy. 14:317-324.

McLaughlin, S.B., Torre Ugarte, D.G. De La., Garten, C.T. Jr., Lynd, L.R., Sanderson, M.A., Tolbert, V.R., and Wolf, D.D. 2002. High-value renewable energy from prairie grasses. Environ. Sci. Technol. 36:2122-2129.

McMillan, C. 1959. The role of ecotypic variation in the distribution of the cental grasslands of North America. Ecol. Monogr. 29: 285-308.

Mehdi, B., Zan, C., Girouard, P., and Samson, R. 1998. Soil organic carbon sequestration under two dedicated perennial bioenergy crops. REAP Canada Final report. Available at http://www.reap-canada.com/online_library/ghg_offsets_policy/

Meisterling, K., Samaras, C., and Schweizer, V. 2009. Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. Journal of Cleaner Production. 17: 222-230.

Mitchell, R., Vogel, K. P., and Sarath, G. 2008. Managing and enhancing switchgrass as a bioenergy feedstock. Biofuels Bioproducts and Biorefining. October: 530-539.

Mohanty, A. K., Misra, M., and Drzal, L.T. 2002. Sustainable bio-composites from renewable resources: opportunities and challenges in the green materials world. Journal of Polymers and the Environment, 10: 19-26.

Moser, L.E., and.Vogel, K.P. 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.

Monti, A., Fazio, S., and Venturi, G. 2009. Cradle-to-farm gate life cycle assessment in perennial energy crops. European Journal of Agronomy, 31:77-84.

Natural Resources Canada. 2008. Available at http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/bioenergy/publications/200843.html

Nemecek, T., and Kagi T. 2007. Life cycle inventories of agricultural production systems. Ecoinvent v 2.0 report no. 15. Agroscope FAL Reckenholz and FAT Taenikon. Dubendorf, Switzerland: Swiss Centre for Life Cycle Inventories.

Ney, R. A., and Schnoor, J. L. 2002. Greenhouse Gas Emission Impacts of Substituting Switchgrass for Coal in Electric Generation: The Chariton Valley Biomass Project.
Available at http://www.cgrer.uiowa.edu/research/reports/iggap/charrcd.pdf

Nielsen, E.L. 1944. Analysis of variation in Panicum virgatum. J. Agric. Res. 69: 327-353.

Nott, D. 2010. Personal communication through e-mails and farm visit.

Olivier, Jos G.J., Maenhout, G.J., Peters, J A.H.W., and Wilson, J. 2011. Long-term trend in global CO2 emissions. A report by PBL Netherlands Environmental Assessment Agency, The Hague, European Union.

Ontario Ministry of Agriculture, Food and Rural affairs (OMAFRA). 2005. Summary Report: Technology Forum-Processing Agricultural Biomass for Combustion Energy to Meet End-User Needs.
Available at
http://www.omafra.gov.on.ca/english/engineer/biomass/techforumrep.htm

Parrish, D.J., and Fike, J.H. 2005. The biology and agronomy of switchgrass for biofuels. Plant Sci.24:423-459.

Parrish, D.J., Wolf, D.D., Taliaferro, C., Hopkins, A.A., Ocumpaugh, W.R., Hussey, M.A., Read, J.C., and Tischler, C.R. 1996. Switchgrass as a sustainable bioenergy crop. Bioresour. Technol. 56: 83–93.

Pelletier, N., Arsenault, N., and Tyedmers, P. 2008. Scenario modeling potential eco-efficiency gains from a transition to organic agriculture: life cycle perspectives on Canadian canola, corn, soy, and wheat production. Environmental management, 42: 989-1001.

Pimentel, D., Hepperly, P., and Hanson, J. 2005. Environmental, energetic and economic comparisons of organic and conventional farming systems. Bioscience, 55:573-582.

Porter, C.L.1966. An analysis of variation between upland and lowland switchgrass, *Panicum virgatum* L., in central Oklahoma. Ecology, 47:980-992.

Qin, X., Mohan, T., El-Halwagi, M., Cornforth, G., and McCarl, B. A. 2006. Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment. Clean Technologies and Environmental Policy, 8:233-249.

Ragauskas, A.J., Williams, C.K., Davison, B.H., Britovsek, G., Cairney, J., Eckert, C.A., Frederick,W.J. Jr, Hallett, J.P., Leak, D.J., Liotta, C.L., Mielenz, J.R., Murphy, R., Templer, R., and Tschaplinski, T.2006. The path forward for biofuels and biomaterials. Science, 311: 484–489.

Ramjeawon, T. 2004. Life cycle assessment of cane-sugar on the island of Mauritius. Int. J Life Cycle Assess. 9:254-260.

Rinehart, L. 2006. Switchgrass as a bioenergy crop. A publication of ATTRA - National Sustainable Agricultural Information Service.

Riley, R.D., and Vogel. K.P. 1982. Chromosome numbers of released cultivars of switchgrass, indiangrass, big bluestem, and sand bluestem. Crop Sci. 22: 1082-1083.

Rochette, P., Worth, D. E., Lemke, R. L., Mcconkey, B. G., Pennock, D. J., Wagner-riddle, C., and Desjardins, R. L. 2008. Estimation of N_2O emissions from agricultural soils in Canada . I . Development of a country-specific methodology. Canadian Journal of Soil Science, 88: 641-654.

Rogner, H.-H., D. Zhou, R. Bradley. P. Crabbé, O. Edenhofer, B. Hare (Australia), L. Kuijpers, and M. Yamaguchi (2007). Introduction. In: Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds.), Cambridge University Press, pp. 95-116.

Samson, R., Girouard, P., Omielan, J., and Henning, J. 1993. Integrated production of warm season grasses and agroforestry for biomass production. Paper presented at Energy, Environment, Agriculture and Industry: The 1st Biomass Conference of the Americas, Golden, CO.
Available at http://www.reap-canada.com/online_library/feedstock_biomass/

Samson, R., Girouard, P., and Chen, Y.1997. Evaluation of switchgrass and short-rotation forestry willow in Eastern Canada as bio-energy and agri-fibre feedstocks. In: Proc. 3rd Biomass Conference of the Americas: Making a Business in Biomass in Energy, Environment, Chemicals, Fibres and Materials, Montr´eal, QC, 145–151. Elsevier Science Limited, Oxford, UK. Available at
http://www.reap-canada.com/online_library/grass_pellets/Evaluation

Samson, R. and Duxbury, P. 2000. Assessment of pelletized biofuels. Final report to Natural Resources Canada, Ottawa, Ont. Available at http://www.reap-canada.com/online_library/feedstock_biomass/

Samson, R., Mani, S., Robert, B., Shahab, S., Diego, Q., Segundo, Q., Veronica, R., and Claudia Ho, L. 2005. The Potential of C4 Perennial Grasses for Developing a Global BIOHEAT Industry. Plant Sci. 24: 461-495.

Samson, R. 2007. Switchgrass production in Ontario: A management guide. A joint report of Agriculture and Agri-Food Canada, REAP Canada and University of Guelph.
Available at http://www.uvm.edu/pss/vtcrops/articles/EnergyCrops/

Samson, R., Bailey, S., and Ho Lem, C. 2007. The Emerging Agro-Pellet Industry in Canada. Paper presented at the 15th European Biomass Conference and Exhibition, Berlin, Germany.
Available at http://www.reap-canada.com/online_library/feedstock_biomass/

Samson, R. 2008. Switchgrass for BioHeat in Canada. Available at http://www.reap-canada.com

Samson, R., Stamler, B., Dooper, J., Mulder, S., Ingram, T., Clark, K., and Lem, C.H. 2008. Analysing Ontario biofuel options: greenhouse gas mitigation efficiency and costs. Final report prepared by Resource Efficient Agricultural Production (REAP) – Canada. For BIOCAP Canada. Available at http://www.reap-canada.com/online_library/grass_pellets/BIOCAP_REAP_bioenergy_policy_

Samson, R. 2009. Establishing Bioheat in Eastern Ontario Utilizing Switchgrass and Agricultural Biomass for Solid Fuel, Final Report Presented to SD&G Community Futures Development Corp. Available at http://www.webtechcanada.com/sdgcfdc/REAPCanadaFinalReport.pdf

Sanderson, M.A., Reed, R.L., McLaughlin, S.B., Wullschleger, S.D., Conger, B.V., Parrish, D.J., Wolf, D.D., Taliaferro, C., Hopkins, A.A., Ocumpaugh, W.R., Hussey,M.A., Read, J.C., Tischler, C.R., 1996. Switchgrass as a sustainable bioenergy crop. Bioresource Technol. 56: 83–93.

Schmer, M. R., Vogel, K. P., Mitchell, R. B., and Perrin, R. K. 2008. Net energy of cellulosic ethanol from switchgrass. Proceedings of the National Academy of Sciences of the United States of America,105:464–469.

Shapouri, H., Duffield, J. A., and Graboski, M. S. 1995. Estimating the net energy balance of corn ethanol. Agricultural economic report 721. Washington, DC: US Department of Agriculture.
Available at http://www.ers.usda.gov/Publications/AER721/

Shapouri, H., Duffield, J. A., and Wang, M.2002. The energy balance of corn ethanol: An update. Agricultural economic report 813. Washington, DC: US Department of Agriculture. Available at http://www.transportation.anl.gov/pdfs/AF/265.pdf

Sims, R.E.H., Hastings, A., Schlamadinger, B., Taylor, G., and Smith, P. 2006. Energy crops: Current status and future prospects. Global Change Biol. 12: 2054–2076.

Sparling, D., Cheney, E., and Cranfield, J. 2010. Not enough green in Canada's bioproduct industry, a report from Richard Ivey School of Business.
Available at http://www.cheminst.ca/index.php?ci_id=2934&la_id=1

Spatari, S., Zhang, Y., and Maclean, H.L. 2005. Life Cycle Assessment of Switchgrass – and Corn Stover-Derived Ethanol- Fueled Automobiles. Environ. Sci. Technol. 39: 9750–9758.

Somerville, C., Youngs, H., Taylor,C., Davis, S.C.,and Long, S.P. 2010. Feedstock for lignocellulosic biofuels. Science, 329:790–792.

Spielmann, M., Dones, R., Bauer, C., and Tuchschmid, M. 2007. Life cycle inventories of transport services. Ecoinvent Report 14 v20. Swiss Centre for Life Cycle Inventories, Dubendorf, Switzerland: Swiss Centre for Life Cycle Inventories.

Stander,W. 1989. Determination of the highest biomass producing plant genera (C_4 grasses) of the world for temperate climates, assessment study for the commission of European communities, Munich, Germany.

Stout, W.L., Jung, G.A., and Shaffer, J.A. 1988. Effects of soil and nitrogen on water-use efficiency of tall fescue and switchgrass under humid conditions. Soil Science Society American Journal, 52: 429–434.

Thomason, W.E., Raun, W.R., Johnson, G.V., Taliaferro, C.M., Freeman, K.W., Wynn, K.J., and Mullen, R.W. 2004. Switchgrass response to harvest frequency and time and rate of applied nitrogen. J. Plant Nutr. 27:1199–1226.

Van den oever, M.J. A., Elbersen, H.W., Keijsers E. R. P., Gosselink, R.J.A., and De Klerk-Engels, B. 2003. Switchgrass (*Panicum virgatum* L.) as a reinforcing fibre in polypropylene composites. Journal of Material Science, 38:3697-3707.

Van der Werf, H.M.G. 2004. Life cycle analysis of field production of fibre hemp, the effect of production practices on environmental impacts. Euphytica, 140:13-23.

Venturi, P., and Venturi, G. 2003. Analysis of energy comparison for crops in European agricultural system. Biomass and Bioenergy, 3: 235-255.

Vogel, K. P., and Jung, H. G. 2000. Genetic improvement of switchgrass and other herbaceous plant for use as biomass fuel feedstock. Final report by USDA-Agriculture Research Service. Available at http://www.ornl.gov/~webworks/cpr/rpt/108995_.pdf

Vogel, K.P.2004. Switchgrass. 561-588 In: L.E. Moser et al., eds. Warm-season (C_4) Grasses. ASA-CSSA-SSSA, Madison, WI.

Vogel, K.P., and Mitchell, R. B.2008. Heterosis in switchgrass: Biomass yield in swards. Crop Sci. 48:2159-2164.

Vowles, A. 2011. Bio-Bins Are U of G Innovation : Canadian retailers sell storage bins made with U of G biocomposite formula. News report, Thursday, May 5, 2011. Available at http://atguelph.uoguelph.ca/2011/05/bio-bins-are-u-of-g-innovation

Wang, M., Saricks, C., and Santini, D.1999. Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emission. ANL/ESD-38. Argonne, IL: Argonne National Laboratory. Available at http://www.transportation.anl.gov/pdfs/TA/58.pdf

Weidema, Bo. P. 1997. Environmental assessment of products. A text book on life cycle assessment. The Finnish Association of Graduate Engineers (TEK), Helsinki, Finland.

Wenzel, H., Hauschild, M.Z., and Alting, L.1997. Environmental Assessment of Products. Methodology, Tools, Techniques and Case Studies, vol. 1. Chapman & Hall, United Kingdom, Kluwer Academic Publishers, Hingham, MA, USA, ISBN 0 412 80800 5.

Wood, S., and Layzell, D. 2003. A Canadian Biomass Inventory: Feedstocks for a Bio-based Economy, Final Report by BIOCAP Canada for Industry Canada. Available at http://www.biocap.ca/images/pdfs/BIOCAP_Biomass_Inventory.pdf

Zou, Y., Xu, H., and Yang, Y. 2010. Lightweight polypropylene composites reinforced by long switchgrass stems. J Poly Environ. 18:464–473.

APPENDIX

Table 4.3 Total impact of all life cycle processes on individual impact categories

Impact category	Unit	Total impact **HS1**	Total impact **HS2**
Global warming	kg CO2 eq	191	204
Acidification	H+ moles eq	58	64
Carcinogenics	kg benzene eq	0.031	0.036
Non carcinogenics	kg toluene eq	190	214
Respiratory effects	kg PM2.5 eq	0.07	0.09
Eutrophication	kg N eq	0.10	0.11
Ozone depletion	kg CFC-11 eq	1.23E-05	1.33E-05
Ecotoxicity	kg 2,4-D eq	8.20	13.80
Smog	g NO_x eq	0.33	0.44

Table 4. 4 Global warming potential (GWP) of life cycle processes

Process	**GWP (kg CO_2 eq)**	**Percentage**
Soil N_2O emission	27.00	13^b-14^a
Land preparation	0.64	**
Seed Sowing	0.39	**
Mowing	1.53	**
Herbicide related	0.77	**
Fertiliser related	125.52	61^b -66^a
Swathing	0.71	**
Raking	1.32	**
Chopping	32.46	16^b -17^a
Loading HS1	0.39	**
Bale Loading HS2	1.15	**
Baling HS2	12.27	6^b
Total HS1	191	100
Total HS2	204	100

** value less than 1%, [a] per cent value for HS1, [b] per cent value for HS2

Table 4.5 Eutrophication Potential (EP) of life cycle processes

Process	**EP (kg N eq)**	**Percentage**
Soil N emission	0.0388	35-38
Land preparation	0.0007	**
Seed Sowing	0.0010	1
Mowing	0.0006	**
Herbicide related	0.0017	1
Fertiliser related	0.0452	41-44
Swathing	0.0004	**
Raking	0.0006	**
Chopping	0.0133	12-13
Loading HS1	0.0003	**
Loading HS2	0.0010	1
Baling HS2	0.0068	6
Total HS1	0.1026	100
Total HS2	0.1100	100

** less than 1%

Table 4.6 Acidification potential (AP) of life cycle processes

Process	**AP (H+ moles eq)**	**Percentage**
Soil N emission	31.22	48[b]-53[a]
Land preparation	0.55	**
Seed Sowing	0.17	**
Mowing	0.18	**
Herbicide related	0.20	**
Fertiliser related	21.05	33 [b] -36[a]
Swathing	0.12	**
Raking	0.10	**
Chopping	5.05	8[b] -9[a]
Loading HS1	0.20	**
Loading HS2	0.49	**
Baling HS2	5.41	8[b]
Total HS1	58.80	100
Total HS2	64.45	100

** less than 1%,%, [a] per cent value for HS1, [b] per cent value for HS2

Table 4.7 Toxicity potential of life cycle processes

Process	Ecotoxicity Potential	Respiratory effects potential	Carcinogenics potential	Non carcinogenics potential
	kg 2,4-D eq (%)	*kg PM2.5 eq (%)*	*kg benzene eq (%)*	*kg toluene eq (%)*
Soil N emission	0.02**	0.00	0.00	1.05**
Land preparation	0.35 (3-4)	0.0023 (2-3)	0.000071**	1.34**
Seed Sowing	0.06**	0.0005**	0.000204**	2.74 (1)
Mowing	0.13 (1-2)	0.0007**	0.000132**	1.54**
Herbicide related	0.23 (2-3)	0.0009 (1)	0.000501 (1.6)	1.84**
Fertiliser related	3.69 (27-45)	0.0507 (53-69)	0.027293 (81-87)	138.27 (65-73)
Swathing	0.12**	0.0004**	0.000070**	0.87**
Raking	0.02**	0.0005**	0.000128**	1.26**
Chopping	3.35 (24-41)	0.0167 (18-23)	0.003004 (9-10)	40.55 (19-21)
Loading (HS1)	0.26 (3)	0.0008**	0.000038**	0.83**
Loading (HS2)	0.86 (6)	0.0015 (2)	0.00008**	6.18 (3)
Baling (HS2)	5.00 (36)	0.0222 (23)	0.002267 (7)	18.23 (9)
Total (HS1)	8.24	0.0736	0.031440	190.29
Total (HS2)	13.83	0.095	0.033707	213.86

**** less than 1%**

Table 4.8 Ozone depletion potential of life cycle processes

Process	**kg CFC-11 eq**	**Percentage**
Land preparation	9.81E-08	**
Seed Sowing	3.95E-08	**
Mowing	2.38E-07	2
Herbicide related	1.68E-07	1
Fertiliser related	6.47E-06	49-52
Swathing	9.10E-08	**
Raking	1.70E-07	1
Chopping	5.01E-06	38-40
Loading HS1	5.98E-08	**
Loading HS2	1.28E-07	**
Baling (HS2)	5.98E-08	**
Total (HS1)	1.23E-05	100
Total (HS2)	1.32E-05	100

Table 4.9 Smog potential of life cycle processes

Process	**g NOx eq**	**Percentage**
Land preparation	0.0127	3-4
Seed Sowing	0.0030	**
Mowing	0.0028	**
Herbicide related	0.0022	**
Fertiliser related	0.2145	49-64
Swathing	0.0018	**
Raking	0.0006	**
Chopping	0.0910	21-27
Loading (HS1)	0.0045	1
Loading (HS2)	0.0096	2
Baling (HS2)	0.1022	23
Total (HS1)	0.3330	100
Total (HS2)	0.4352	100