Interuniversity Research Centre for the
Life Cycle of Products, Processes and Services

ONTARIO SWITCHGRASS AND MISCANTHUS FARM GATE CARBON FOOTPRINTS

FINAL REPORT – OCTOBER 2013

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To the attention of Charles Lalonde

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Executive summary

The marketing of biomass as a green alternative is important in today's market, whether for combustion purposes, bioproduct fabrication, or for bioprocessing into transportation fuels or green chemicals. The ability to provide farm gate greenhouse gases (GHG) profile -or carbon footprint- information based on inputs and modern production practices represents an important element in the marketing of purpose grown biomass in the future. Consequently, there is an opportunity for Ontario producers to move into new energy crop markets provided that adequate environmental information with respect to GHG emissions from their production is documented for end-users.

The purpose of this study is to calculate the carbon footprint of biomass at the farm gate and document the model used to derive the calculations. An additional outcome has been the determination of the carbon sequestration potential for the two biomass crops examined.

This carbon footprint study strictly follows the framework from ISO14040:44 Standards on LCA. Also, it is compliant with guidelines specific to agricultural products and to agricultural products intended for energy use, such as the two GHG Protocol's Agricultural Guidance and Product Standard and to the European Commission's Renewable Energy Directive requirements.

The carbon footprint is reported to the functional unit: ***"1 kg dry matter of Switchgrass or Miscanthus agricultural biomass, baled, at farm gate, produced in Ontario according to best management practices as of 2013"***. It is calculated over the lifetime of the perennial crops (15 years), including land preparation, planting and establishment years. Primary data have been collected from several Ontario biomass producers for fieldwork operations, and best management practices are from an Ontario study (Engbers, 2012), while some other data and assumptions have been validated by the OFA and the OSCIA (2013).

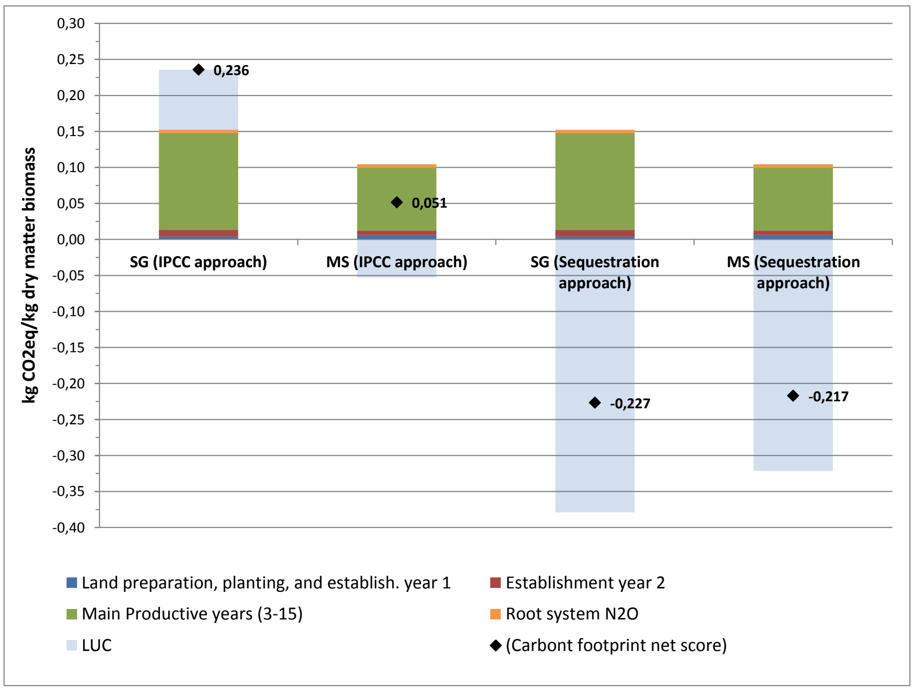
N_2O field emissions are calculated according to a Tier-2 Canadian-specific IPCC methodology (Rochette et al. 2008). Land use change (LUC) impact is estimated using two different approaches for a better evaluation of the sensitivity of results to the uncertainty related to this source of GHG. The first approach is based on the IPCC guidelines and weighing factors for assessing the soil organic carbon (SOC) stock change. The sequestration approach assumes a positive SOC change (i.e. carbon sequestration) derived from a literature review, giving an average net sequestration rate from all carbon stocks (SOC and vegetation) of 0.55 and 0.7 tonne C/ha.year for Switchgrass and Miscanthus, respectively.

The Figure below presents the contributions to the carbon footprint calculated with the two different approaches for LUC. LUC contribution can be so high that it becomes critical how LUC GHG is estimated. In the case of the IPPC approach for Switchgrass, LUC impact is a net emission and contributes for 35% of the footprint, N_2O emission for 35% as well, fertilizer supply for 11%, and the baling and the bale handling operations for 7%. For Miscanthus, LUC offers a net credit corresponding to 51% of GHG emissions, while the other stages contribute for 52%, 17%, and 13% of the emissions, respectively. The LUC credit is obtained thanks to the higher carbon

sequestration capacity of Miscanthus' un-harvested vegetation and to the higher share of cropland as a previous land use than for Switchgrass (90% vs. 75%) which limits SOC loss.

In the case of the carbon sequestration approach scenario, LUC offers an important GHG credit and the resulting carbon footprint is negative and similar for both biomass, about -0.22 kg CO_2eq/kg dry matter biomass.

One key recommendation for a more robust assessment of biomass carbon footprint is to gather comprehensive Ontario-specific data for above- and below-ground crop components' mass and carbon and nitrogen contents, long term soil organic carbon content of biomass cropland and of the previous land uses.



Switchgrass (SG) and Miscanthus (MS) carbon footprint according to two different accounting for LUC: the IPPC approach and the carbon sequestration approach (calculated carbon stock net change of 0.55 and 0.7 tonne C/ha.year for SG and MS, respectively).

A recommendation to producers would be to promote lower fertilizer rates without sacrificing yield, which will also increase profitability. Yearly soil analyses should help determine an optimal fertilizer rate. Conversely, sensitivity of the carbon footprint to stands' lifetime is not very significant. Even more insignificant are stands' establishment failure rate and practices for weed management and bale storage. The single fieldwork on which to focus for improvement although limited – would be the diesel consumption for baling.

Switchgrass and Miscanthus are perennials known as low-input crops (low fieldwork, low N input,). This study demonstrates that GHG impact from producing such a biomass in Ontario is indeed not governed by fieldworks but mostly by soil N_2O emissions concomitant to N inputs and by fertilizer production. Considering LUC can significantly influence the biomass carbon footprint, positively or negatively, a conservative positioning is to consider a carbon footprint about 0.24 kg CO_2eq/kg dry matter biomass for Switchgrass and about 0.05 kg CO_2eq/kg dry matter for Miscanthus (IPCC approach scenario).

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Abbreviations and Acronyms

AAFC	Agriculture and Agri-Food Canada
B2B	Business to Business
B2C	Business to Consumer
C	Carbon
CF	Carbon Footprint
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
dm	Dry matter
FQD	Fuel Quality Directive (European Commission)
GHG	Greenhouse gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LUC	Land use Change
MS	Miscanthus
N	Nitrogen
NH_3	Ammonia
N_2O	Nitrous oxide
NO_3^-	Nitrate
OFA	Ontario Federation of Agriculture
OSCIA	Ontario Soil and Crop Improvement Association
PCF	Product Carbon Footprint
RED	Renewable Energy Directive (of European Commission)
SG	Switchgrass
SOC	Soil Organic Carbon

1 Introduction

The marketing of biomass as a green alternative is important in today's market, whether for combustion purposes, bioproduct fabrication, or for bioprocessing into transportation fuels or green chemicals. The ability to provide farm gate greenhouse gases (GHG) profile -or carbon footprint- information based on inputs, modern production practices and pre-processing to the farm gate represents an important element in the marketing of purpose grown biomass in the future. Consequently, there is an opportunity for Ontario producers to move into new energy crop markets provided that adequate environmental information with respect to GHG emissions from their production is documented for end-users. Within this context, the Ontario Federation of Agriculture (OFA) has commissioned the CIRAIG for:

- suggesting an appropriate recognized carbon footprinting calculation method recognized internationally on which to base the calculation;
- calculating the carbon footprint of switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus* spp.), two purpose-grown biomass crops produced in Ontario, considering best management practices developed from the feedback from the Ontario Soil and Crop Improvement Association (OSCIA);
- providing a database supporting the calculation of the farm gate carbon footprint of the two biomass crops.

This report presents:

- A descriptive review of current carbon footprint methodologies applicable to agricultural production (**Chapter 2**).
- The goal and scope of the carbon footprint study (**Chapter 3**).
- The carbon footprint results, their interpretation and recommendations (**Chapter 4**).
- The resulting conclusions (**Chapter 5**).

This study has been conducted according to the requirements of ISO 14040 & 14044 (ISO 2006a, b) for internal use by the OFA.
This technical report is therefore the final report of the LCA study. Results were also provided to the OFA as a presentation and Microsoft Excel workbooks. Appendix A presents a detailed table of the different carbon footprint methodologies reviewed, with their common and distinctive features. All documents consulted during the project are listed in the References section.

2 Review of current carbon footprint methodologies and guidelines

A product carbon footprint (PCF) analysis assesses the greenhouse gas emissions throughout the complete life cycle of a product. As such, it can be considered as a subset of the life cycle assessment methodology since it focuses exclusively on GHG emissions whereas LCAs **assess the potential impact a product on a broad range of parameters**. PCF is used as a measure of impact for climate change purposes.

Over the past few years, there has been a growing trend to measure PCF. Several methodological guidelines and framework have emerged for accounting the life cycle greenhouse gas emissions of a product, its carbon footprint *per se*.

This literature review conducted to support this carbon footprint study for Switchgrass and Miscanthus, with the perspective of an eventual usage in a variety of bio-based products, has included the following:

- ***Framework methodologies for life cycle assessment***
  - ISO14040:44 (2006)
  - European Commission/Joint Research Center (2010) ILCD Handbook
  - European Commission (2013) Product Environmental Footprint Methodology
  - AFNOR (2011) BPX30-323 – General principles for an environmental communication on mass market products – Partie 0 : Principes généraux et cadre méthodologique
- ***Framework methodologies specific for Carbon Footprint***
  - ISO (2013) TR ISO14067 Carbon footprint of products — Requirements and guidelines for quantification and communication
  - BSI (2011) PAS2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services
  - WRI and WBCSD (2011) Greenhouse Gas Protocol – Product Life Cycle Standard
- ***Sectoral guidance (related but not specific)***
  - WRI and WBCSD (2013) GHG Protocol – Agricultural Guidance
  - Envifood Protocol (for farming upstream processes)
  - AFNOR (2011) BPX30-323 – General principles for an environmental communication on mass market products – Part 15: Methodology for the environmental impacts assessment food products
  - BioGrace Harmonized Calculation of Biofuel GHG Emissions in Europe – version 4c
  - Roundtable on Sustainable Biofuels (RSB) GHG Calculation Methodology – Version 2.0

A thorough comparison of these references is presented in Appendix A.

2.1 Suggested Study Framework

As the OFA requested that the PCF calculations for both miscanthus and switchgrass be compatible with European regulation requirements, a methodology combining several guidelines is hereby proposed:

- ***GHG Protocol agricultural guidance***: general framework calculation, adapted to a product perspective;
- ***BioGrace guidance:*** in order to show compliance with sustainability criteria as defined in national legislation implementing the European Renewable Energy Directive (2009/28/EC). In general, the BioGrace GHG calculation rules are in line with the standard that is prepared under CEN TC 383 “Sustainably produced biomass for energy use”; and
- RSB guidelines on some specific issues where BioGrace is not suitable.

2.2 Goal and scope

The different guidelines may not be suited to all kinds of analysis for various products. For example, standards providing guidance for LCA can be used for product carbon footprint whereas guidelines specific to carbon footprint cannot be used for LCA. All standards used in this study meet criteria for carbon footprint analysis and publication.

Furthermore, the suggested guidelines may be used for two different levels of analysis: at the product level and at the corporate level. While some guidelines may be used for both, others were designed specifically for a given level. However, an organisation level’s guidelines can be adapted to deal with product carbon footprint as well.

➔ The multiple methodological approaches hereby proposed is specific to GHG accounting and may not be used to perform an LCA. On the other hand, the GHG Protocol for-Agricultural Guidance is meant to focus on a corporate approach of GHG accounting instead of a product approach. However, the calculations can easily be adapted to a product approach.

Finally, frameworks guidelines, such as ISO 14040, the PEF methodology or TR ISO 14067, remain general and do not provide requirements as to how to implement CF calculations for a specific product or a product category. Hence, additional guidance can be provided by product category rules or sectoral guidance in order to define how to deal with methodological issues such as the unit of analysis, system boundaries, data selection and computation.

➔ In order to be provided with specific guidance as possible for switchgrass and miscanthus, the agricultural guidance from the GHG protocol initiative was selected. On the other hand, BioGrace is made specifically for agricultural products meant to become biofuels as the GHGP-AG does not have any specific requirements regarding the use phase.

Most of the standards do not have a unique purpose regarding the communication of a PCF **value**. In fact, it is more often related to the scope of the study itself. However, some standards were specifically designed to provide accounting guidelines with the perspective of a specific communication mean. As an example, BPX30-323 provides guidance for footprinting with the perspective of a “business-to-consumer” communication. This can also be the case of standard underlying a certification scheme such as the RSB GHG Calculation Methodology.

➔ GHG-P-AG mainly aims at a communication at a Business to business (B2B) level. On the other hand, BioGrace is used to show compliance with sustainability criteria as defined in national legislation implementing the Renewable Energy Directive (RED) from the European Commission and FQD sustainability criteria.

General framework guidelines do not provide specifications regarding the **functional unit** to be used for calculations, only referring to the fact that they shall be consistent with the goal and scope of the study. However, sectoral guidance specifies the functional unit.
When the study is meant for Business to Consumer (B2C) communication-related applications, the functional unit shall be defined as a unit of production or a portion.
When the product is an intermediate one, the final use and function are unknown. In such cases, a functional unit cannot be defined and the unit of analysis underlying the calculation will hence be the reference flow. These PCF studies are often meant for B2B communication related applications.

➔ As the GHGP-AG is initially meant to focus on a corporate level, the unit of analysis is usually set to overall production over one or several years. As BioGrace works at a product level, the calculations are set up over one unit of production.

Life cycle assessment standards and methodological guidelines such as ISO 14040:44 or the ILCD Handbook usually define the **setting of system boundaries** as an iterative process where all processes linked to the product supply chain shall be included. LCA framework underlying communication objectives such as the PEF or the French BPX30-323 methodologies or product category rule will on the other hand provide specifications as to which processes may be excluded – mainly following the purpose of favoring the comparability of communicated results.
The system boundaries may be defined from a cradle-to-grave or cradle-to-gate perspective which will depend on the product to be assessed and the communication target.
The GHGP-AG defines two main categories of boundaries: organisational and operational boundaries. First, the organisational boundaries define when a company must endorse the responsibility of a GHG emission. Organisational boundaries are often set with regards to the operational control the company will have on the source of emission. Within these organisational boundaries, the operational boundaries define three scopes of accounting for GHG emissions. Scope 1 emissions are direct emissions; scope 2 are indirect emissions from the production of purchased electricity, cold, heat and steam; whereas scope 3 emissions are all the other indirect emissions emitted throughout the supply chain.

➔ The GHGP-AG specifies 2 categories of emissions within scopes 1, 2 and 3: mechanical and non mechanical sources. They are detailed for the following 3 stages: preproduction, production and post production (when known). BioGrace requires the system boundary to be life cycle based.

The **cut-off criteria** define which inputs will be taken into consideration in the assessment. According to ISO14040:44, initial identification of input based on mass alone may lead to significant omissions; energy and environmental significance should also be used as cut off.

➔ The GHGP-AG is aligned with the GHGP-PS. It does not set any cut off rule as all processed attributed to the product system must be included and all exclusions duly justified. An estimation proving the insignificance of a process may be used, based on mass, energy or volume and environmental significance. BioGrace excludes emissions from the manufacture of machinery and equipment as well as inputs which will have little or no effect on the resultants (e.g. chemicals used in low amounts in processing)

In LCA, the **temporal horizon** classically encompasses the complete life cycle of a product as well as its emissions to nature taken into account under the perspective of impact assessment methodologies.
However, for carbon footprinting application and from a product perspective, the temporal horizon will be the amount of time it takes for the product to complete a global life cycle and throughout which, emissions will occur. The emissions are to be assessed under the 100 year time horizon of IPCC (GHGP-PS, 2011).
For agricultural products, the base period should be representative of an entity's climate impact. It should not be an individual crop year or production season (for livestock) because the effects of seasonal management activities may not be reflected in the base period. Hence, companies should average GHG flux data from multiple, consecutive years to form a more representative base period.
Following the IPCC (2006) guidance, the temporal horizon for calculating GHG from land use change is usually of 20 years.

➔ This study encompasses a crop cycle of 15 years.

2.3 Life cycle GHG emissions

GHG emissions calculations are based on **primary and secondary data.** Primary data are measured, calculated or estimated from the production sites associated with the unit processes within the system boundary. Secondary data are derived from other sources such as literature or databases.
ISO standards do not provide requirements regarding the use of one or another. ILCD Handbook and PEF methodology require primary data for all foreground processes and for background data when appropriate. Generic data may be used for foreground processes since they would be more representative.

➔ The GHGP-AG proposes a procedure to prioritize data collection. Using IPCC (2006), BioGrace remotely proposes the use of tier 1 data factor from the IPCC (2006). However, whenever possible, region specific tier 2 data should be prioritized.

When calculating a PCF, there are several ways of dealing with **multifunctional processes** (e.g. a cogeneration unit will provide energy and steam – how do you allocate the environmental impact between both items: energetic allocation, economic allocation with regards to the selling price?).
Most methodologies are aligned with ISO 14044 recommendations. Hence, companies shall avoid allocation wherever possible by using process subdivision, redefining the functional unit, or using system expansion. If allocation is unavoidable, companies shall allocate emissions and removals based on the underlying physical relationships between the studied product and co-product(s). When physical relationships alone cannot be established, companies shall select either economic allocation or another allocation method that reflects other relationships between the studied product and co-product(s).

➔ The GHGP-AG is aligned with that approach whereas BioGrace requires an allocation based on the energy content.

Apart from BioGrace, all standards and guidelines require that **emissions off setting and savings** shall not be included in the assessment.

- ➔ More specifically, BioGrace considers that based on the RED Directive from the European Commission emission saving from excess electricity from cogeneration shall be taken into account. It shall be considered in relation to the excess electricity produced by fuel production systems that use cogeneration except when the fuel used for the cogeneration is a co-product other than an agricultural crop residue. In accounting for that excess electricity, the size of the cogeneration unit shall be assumed to be the minimum necessary for the cogeneration unit to supply the heat that is needed to produce the fuel. The greenhouse gas emission saving associated with that excess electricity shall be taken to be equal to the amount of greenhouse gas that would be emitted when an equal amount of electricity was generated in a power plant using the same fuel as the cogeneration unit.

Some methodological issues are specific with GHG emissions calculations for the agricultural sector and products. The following paragraphs highlight them.

Carbon storage sequestration and delayed emissions

Except for ISO14040:44, which do not provide any provisions on that matter, most standards require carbon storage to be reported separately if calculated.

ILCD Handbook, PEF methodology, BPX30-323 and TR ISO14067 refer to the specificities of goal and scopes and product category rules for including them in calculations.

PAS2050:2011, GHGP-PS, Envifood Protocol BioGrace and RSB require carbon storage to be included in the inventory but reported separately.

- ➔ GHGP-AG requires to report net CO_2 fluxes to/from carbon pools, but not actual stock data themselves. Changes in the following carbon stocks shall be accounted for: (a) Organic carbon stocks in mineral and organic soils (b) Below-ground and above-ground woody biomass stocks (c) DOM stocks, if relevant. The CO_2 fluxes from these changes are reported separately in a special 'Biogenic C' category within inventories. The BioGrace calculations are based on a tier 1 approach from the IPCC (2006) reports.

Biogenic CO_2

Except for ISO14040:44, which do not provide any provisions on that matter, most standards require all CO_2 emission from biogenic sources to be reported separately.

RSB methodology assumes biogenic carbon emissions to be carbon neutral as CO_2 was taken up from the atmosphere to grow the biogenic material. Therefore, biogenic carbon is not assigned any CO2 emissions from fuel use; only fossil fuel is assigned CO_2 emissions.

- ➔ The GHGP-AG requires that biogenic CO_2 emissions shall be reported separately from the scopes and any other memo items, within a special category "biogenic carbon". Biogenic CO_2 emissions from natural disturbances and unmanaged lands may be excluded from inventories. Biogenic CO_2 fluxes from land use change and agricultural activities should be reported separately.

Emissions from direct and indirect land use change (LUC)

All guidelines and standards deal with the calculation of emissions from direct land use change using the IPCC (2006) guidance. Emissions are allocated to the product for 20 years after the LUC.

At the moment, no internationally agreed method provides guidance for calculating emissions from indirect land use change. Hence, when **referred to in standards and guidelines**, indirect LUC is excluded from the assessment, apart from the ILCD Handbook which included indirect LUC for consequential modeling LCAs.

N_2O, Ammonia and Nitrate emissions from field

Most methodologies do not provide specific guidance. However, when guidance is provided, it refers to IPCC (2006).

- ➔ The GHGP-AG prioritizes field emissions, the use of emission factors, empirical models and process-based models to assess N_2O emissions from field.
- ➔ The RSB provide specific guidance for ammonia and nitrate emissions calculations, in contrast to other standards.

2.4 Life cycle GHG emissions impact assessment on climate change

The impact assessment model defines characterization factors which translate a GHG emission to an impact on climate change: **these are called global warming potential**. As not all GHG have the same radiation potential, they have different global warming potentials.

ISO14040:44, ILCD Handbook, GHGP-AG and CSBP Provisional Standard only require the impact assessment model (thus characterization factors – Global warming potentials) to be defined and referenced. All other standards and guidelines require the use of IPCC2007 global warming potentials.

- ➔ The GHGP-AG requires the characterization factors to be referenced with no preference whatsoever on the choice. BioGrace requires the use of IPCC2007 global warming potential.

3 Goal and scope of the study

This chapter describes the goal and scope of the study, stating the methodological framework for the following LCA stages.

3.1 Objective and intended application

This investigation aims to calculate the carbon footprint of switchgrass and miscanthus, two purpose-grown biomass crops produced in Ontario.
More specifically, the **objectives** of the study are:

I. To define the GHG profiles of the systems defined by the cradle-to-farm gate production of miscanthus (*Miscanthus* spp.) and switchgrass (*Panicum virgatum* L.) based on best management practices currently developed in Ontario (Engbers, 2012);
II. To perform a contribution analysis and identify the key parameters/hotspots of the systems;
III. To provide an assessment of the influence of several key variables or characteristics, namely the stands' establishment failure rate, the stands' lifetime, the fertilizer rate, the yield, the amount of above-ground crop residues returned to soil, the share between chemical and mechanical weed control, the share between field storage and building storage of biomass bales;
IV. To identify aspects that may require further exploration beyond what is achieved in this study.

The results of this study are intended for internal use by the OFA and its members to improve understanding of their products and systems, identify hot spots and potential problems, identify improvements opportunities, and to assist in their purchasing decisions. They are not intended for public disclosure or marketing.
According to ISO standards, LCA critical reviews are optional when the results are intended for internal use. However, such a review is mandatory prior to public communication (e.g. environmental product declarations according to the ISO 14020 standards or comparative assertions disclosed to the public according to the ISO 14040 standards). Moreover, it is an important step to enhance validity and credibility and improve public acceptance of the results. An internal review by CIRAIG has been conducted on the current study. If the OFA would consider using its results publicly, an external review could be conducted by an external LCA expert and/or a committee of stakeholders. This kind of review facilitates understanding and enhances the credibility of LCA, for example, by involving interested parties.

3.2 General description and context of the studied products

Miscanthus and switchgrass are perennials C4 grasses that are ideal bioenergy crops because of their moderate to high productivity, stand longevity, high moisture and nutrient use efficiency, low cost of production and adaptability to marginal soils (Samson et al., 2009). As part of the OFA's Overall Biomass

Project[1] and with the collaboration of the OSCIA, production practices at the field scale have already been documented with more than 20 Ontario producers participating on the establishment and harvesting of agricultural biomass over 700 acres (Engbers, 2012). Actual practices are steadily improving from year to year based on the gained experience. Much of the prior knowledge comes from previous plot scale experiments, e.g. aggregated by Samson (2007) for switchgrass, from literature review (Kludze et al., 2011) and also reported by Engbers (2012). For instance, delaying harvest from the fall to the spring allows nutrient cycling to the root system, hence a reduced removal rate from the field and a reduced content in chloride and potassium in harvested material that can cause clinker problems and corrosion in boilers (Engbers, 2012; Samson et al., 2009). Also, in some cases, mowing during the first establishment years proves to effectively control weed development and avoid additional pesticides application (Engbers, 2012).

Miscanthus and Switchgrass production is most likely to be located and expected to be developed in south-central and south-eastern Ontario, more specifically within ecoregion 5E of the Ontario Shield ecozone, and ecoregion 6E and 7E of the Mixedwood Plains ecozone (Figure 3-1).

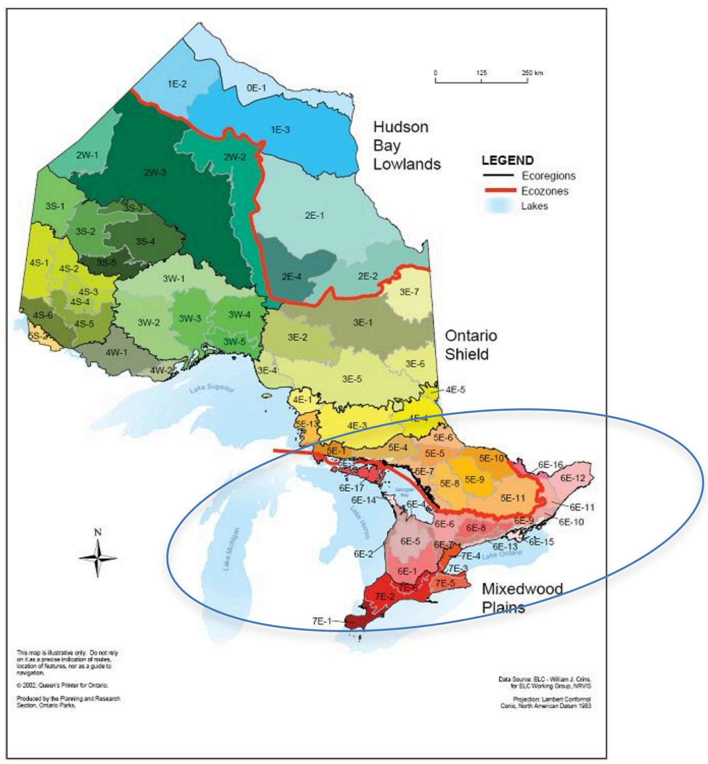

Figure 3-1 : Ontario ecosystems classification: ecozones, ecoregions and ecodistricts (Crins et al., 2009), with delimitation of biomass cropping area.

[1] http://www.ofa.on.ca/issues/overview/biomass

Both perennial crops are either cultivated on cropland of low yield or on pasture or abandoned land converted to biomass production. Generally, they tolerate cold and water stress conditions; adaptability to marginal soil is high; nutrient input is low thanks to the recycling of above-ground vegetation nutrient to roots; and there is no known major pests and/or diseases (Kludze et al., 2011). First, cultivation involves **land preparation**, which tillage level depends on previous land use, and an herbicide chemical burn down. The grasses are then **seeded** (switchgrass) or **planted** with transplant plugs or rhizomes (miscanthus), usually between May and June. The first two years is the **establishment phase** when stands are establishing, and during which weed control (chemical and/or mechanical) is critical, biomass yield is low (to very low the first year especially on marginal land), and establishment failure can occur. The subsequent years compose the **productive phase** (year 2 maybe a productive year at reduce yield), when the annual productive yield is reached, and during which operations are limited to a minimal weed control, fertilization maintenance, cutting and harvesting. All field operations can be carried out with normal farm equipment. Figure 3-2 presents the timeline of perennial crops cultivation, which usually lasts for around 15 years (Kludze et al. 2011).

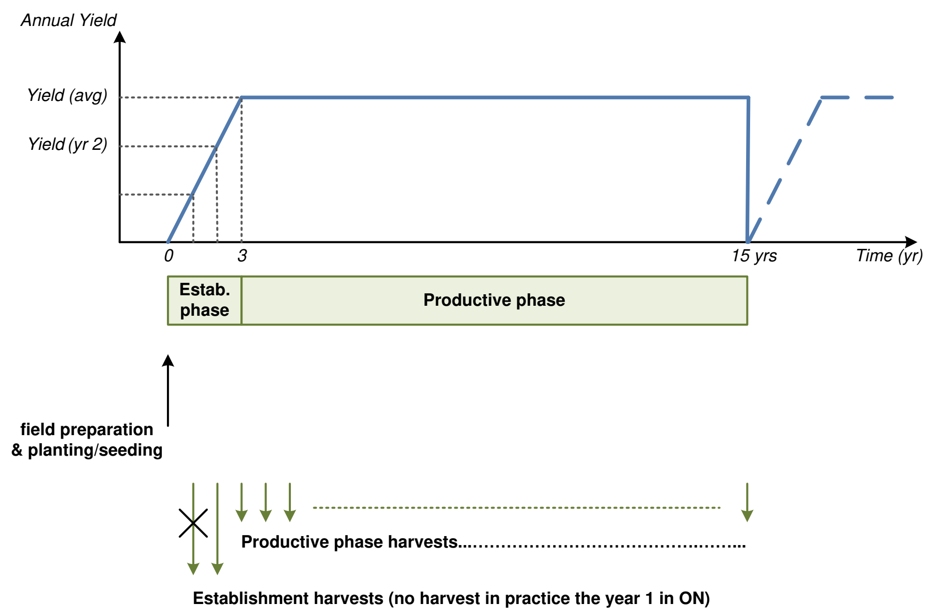

Figure 3-2 : Timeline for miscanthus and switchgrass perennial cropping.

3.3 System function and functional unit

The studied systems are evaluated here on the basis of the **function**: "*producing purpose-grown herbaceous biomass in Ontario that could be used for combustion purpose, bioproduct fabrication, or for bioprocessing into transportation fuels or green chemicals*".

It should be noted that biomass production and markets are still in infancy in Ontario. Current uses of biomass also include livestock bedding, dairy feedstock, substrate for mushroom, and mulching.

The **functional unit,** i.e. the reference to which all input and output data are normalised, is defined here as:

"1 kg dry matter agricultural biomass, baled, at farm gate, produced in Ontario according to best management practices as of 2013".

Two independent systems are defined for the two biomass crops that can respond to this function:

- The **Miscanthus system (MS)**, which produces miscanthus biomass.
- The **Switchgrass system (SG)**, which produces switchgrass biomass.

Reference flows involve the area of each of the two biomass systems needed to perform the function studied. Taking into account the performance characteristics/key parameters of each system, it is assumed that the functional unit above is fulfilled by the cropping of the following area (i.e. reference flows) (Table 3-1):

Table 3-1 : Key parameters and reference flows

System	Key parameters	Reference flow (land use)*
Miscanthus	Productive yield (from year 3) : 13590 kg biomass/ha Yield during establishment year 1 : 0 kg/ha (0%) Yield during establishment year 2 : 6795 kg/ha (50%) → *Average yield = [0+6795+(13590*13)]/15 = 12231 kg/ha* Moisture content : 13 kg water/100 kg biomass Stand lifetime : 15 years	Land provision (transformation) : 1/[0.87*(12231*15)] = 6.265 10^{-6} ha/kg dry matter biomass Land occupation : 15/[0.87*(12231*15)] = 9.398 10^{-5} ha.yr/kg dry matter biomass
Switchgrass	Productive yield (from year 3) : 8650 kg biomass/ha Yield during establishment year 1 : 865 kg/ha (10%) Yield during establishment year 2 : 4325 kg/ha (50%) → *Average yield = [865+4325+(8650*13)]/15 = 7843 kg/ha* Moisture content : 10 kg water/100 kg biomass Stand lifetime : 15 years	Land provision (transformation) : 1/[0.9*(7843*15)] = 9.445 10^{-6} ha/kg dry matter biomass Land occupation : 15/[0.9*(7843*15)] = 1.417 10^{-4} ha.yr/kg dry matter biomass

*: The provision of land is the land transformed from a previous land use (e.g. annual crop, grassland, abandoned land) required to produce 1 kg of dry matter biomass (the functional unit). It is calculated by dividing the total area by total lifetime production. Land occupation considers the duration of land use (taking the time from first soil cultivation until last harvest into account) and the yield per ha over that time. Land is occupied for the same duration as the stand lifetime, i.e. no previous management like a fallow year is assumed. Land occupation is expressed as ha.yr/kg dry matter biomass.

More details on the assumptions used for the calculation of the amount of these reference flows and other key activities data are presented later on in Table 3-2 and Table 3-3.

3.4 Multifunctional processes and allocation rules

LCA does not study products on their own but considers them through the function(s) these products fulfill. Therefore, multifunctional systems or processes must be considered with care. Secondary functions include the production of co-products and the generation of by-products that can be valorized (through recycling for example). The systems under study do not provide agricultural co-products or by-products although cropping such perennials provides services like erosion and leaching prevention but these are not within the scope of this GHG assessment. Similarly, even though residues left on the field after biomass harvest provide nutrients cycling for next growth season, these latter are not considered co-products for two reasons:

- They do not exit system boundaries (described below) and remain on the same field, allowing a decrease of nutrients input the next season;
- Temporal boundaries encompass the whole lifetime of perennials (Figure 3-2).

In addition to these agricultural considerations, the systems can be generating material wastes, such as plastic tarps used to cover bale piles during storage, which can be collected and then recycled out of the farm. Only very few biomass producers actually use such plastics and those were omitted from the assessment.

3.5 System Boundaries

The system boundaries identify the life cycle stages, processes and flows considered in the carbon footprint study and should include all activities relevant to the attainment of the study objectives and therefore necessary to carry out the studied function. The following paragraphs present a general description of the systems and the temporal and geographical boundaries of the study.

3.5.1 General system description

Note also that the life cycle stages of the systems under study are the **foreground systems**, while the **background systems** consist in all the supply and waste management processes involved in every of these stages. Figure 3-3 illustrates the boundaries of the systems studied.

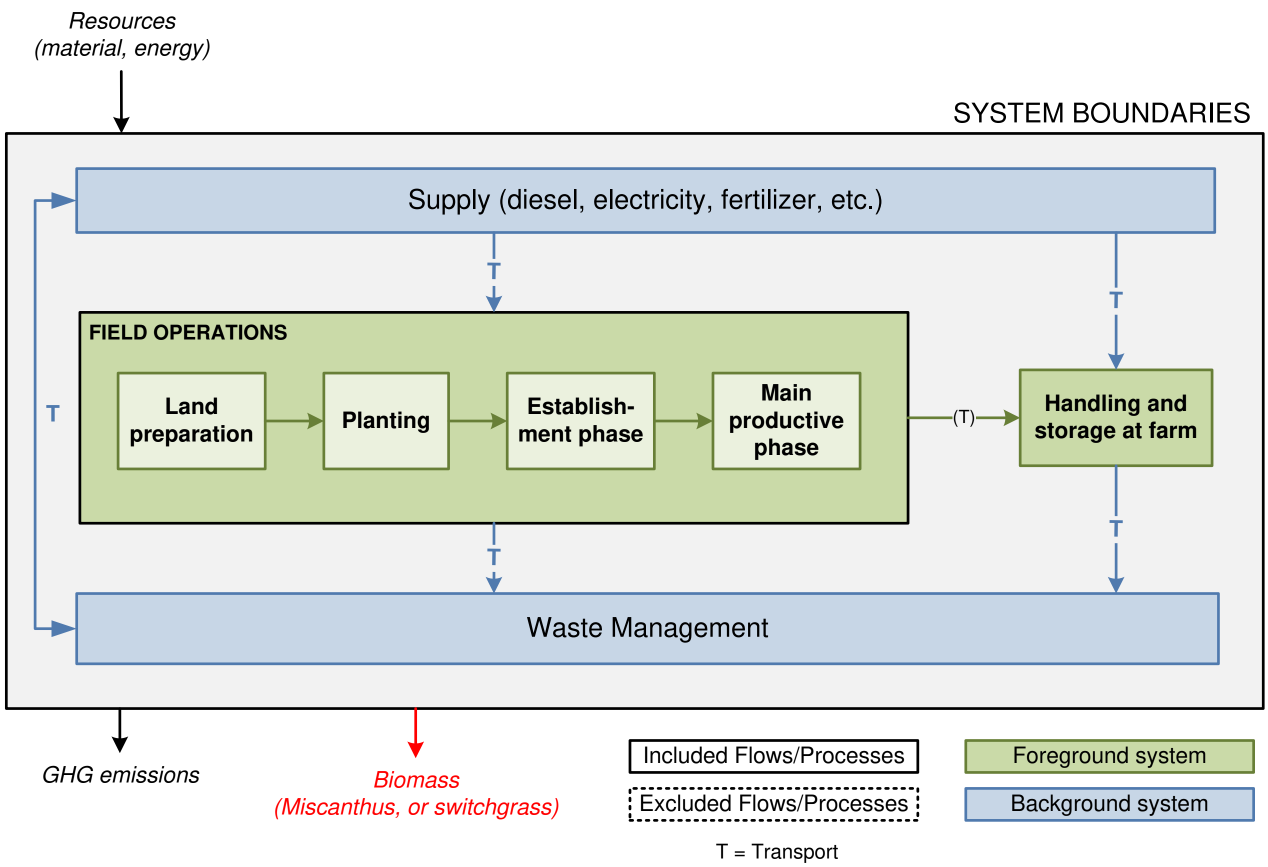

Figure 3-3 : Main life cycle stages included in system boundaries.

The **Land preparation** sub-system includes soil cultivation and the chemical burn down of weeds, so as to make the field ready for the planting. It includes machinery operation for tillage (usually disking) and spraying.

The **Planting** sub-system pertains to the seeding of switchgrass seeds or the transplanting of miscanthus plugs or rhizomes. It includes all machinery operations for seeding or transplanting. In case of switchgrass, direct seeding can be favored by producers, especially if no stubble is to be ploughed under and on difficult marginal and stony fields; this makes the soil cultivation and the seeding a single operation and reduces labour and cost burdens. Seeds and rhizomes production is included in this sub-system. Switchgrass seeds are now produced locally in Ontario (Engbers, 2012). Miscanthus rhizomes are assumed to be produced from a dedicated field where rhizomes are harvested instead of the stem at year 3 of the cycle with a cultivator to lift the rhizomes and a potato planter to separate the soil from the rhizomes (Hamelin, 2011).

The **Establishment** sub-system pertains to the first two years of cropping after planting, with harvest at reduced yield. A weed control operation is included (a mix of practices is considered for pesticide spraying and mechanical mowing), as well as urea fertilizer application (except the first year).

The **Productive phase** sub-system pertains to all subsequent years of production up to 15 years. It includes recurrent operations for nitrogen fertilization, biomass harvesting and baling. Best practice for switchgrass is fall cutting of stands, overwintering of swaths and spring harvesting, whereas miscanthus is overwintered on stands and cut and harvested in spring.

Lastly, the **Handling and storage phase** sub-system occurs every year when harvest is considered as a function of the amount of harvested biomass, and pertains to the loading of biomass bales and their transportation for storage under covered building at farm yard.

The **Supply** and **Waste management** sub-systems respectively pertain, for each of the five preceding sub-systems, to all of the activities that stem from:

- Resource procurement (water, energy, chemicals, materials), including the extraction, treatment and transformation of natural resources and the various transports to the farm.
- The transport and treatment/management of the waste generated during any of the product's life cycle stages, taking all of the possible recovery options into account.

Within each of these stages, the LCA also considers all identifiable "upstream" inputs to provide the most comprehensive view of the system. For example, when considering diesel used for tractors, not only are the combustion emissions and diesel used by the tractor considered, but also the additional processes and inputs needed to produce that diesel. In this way, the production chains of all inputs are traced back to the original extraction of natural resources.

Foreground processes that were included in the system boundaries are detailed in the following section 3.6. Any combined production, such as nurse cropping on the same field as biomass has been excluded. Overheads, i.e. farm-office activities and other services were also excluded because no data were readily available. No cut-off criteria were used. Therefore, all inventory data available were included into the system modeling.

3.5.2 Temporal and geographical boundaries

According to the functional unit, this LCA is representative of the Ontario context in 2013 and for a certain period afterwards providing the data and assumptions used to represent current and recommended best management practices remain relevant and representative of the future context.

It should be noted, however, that some processes within the system boundaries may take place anywhere or anytime, as long as they are needed to achieve the functional unit. For example, the processes associated with the supply and the waste management can take place in Ontario or elsewhere in the world. In addition, certain processes may generate emissions over a longer period of time than the reference year. This applies to landfilling, which causes emissions (biogas and leachate) over a period of time whose length (several decades to over a century/millennium) depends on the design and operation parameters of the burial cells and how the emissions are modeled in the environment.

3.6 Life cycle inventory data, sources and assumptions

LCI data collection mainly concerns the materials used, the energy consumed and the wastes and emissions generated by each process included in the system boundaries. The data collection process is an important step that has been conducted iteratively between CIRAIG and the OSCIA, the OFA and the biomass producers involved in the field scale development project. The quality of LCA results are dependent on the quality of data used in the inventory analysis. Therefore, for this investigation every effort has been made to implement the most robust and representative information available. This study was conducted in order to focus on **primary data** easily available at first, followed by a more detailed data collection for specific processes/key parameters. Specifically, biomass producers were surveyed from May to July 2013 about machinery use. This data collection process complements the large dataset gathered from the same producers through years by the OSCIA in the context of the Agricultural Biomass Research and Development Project about agronomic and production practices (Engbers, 2012). It should be noted that this project is experimental by nature and aims at determining the best practices for recommendations to current and future biomass producers. Hence, raw data from Engbers (2012) display large variability and cannot be simply averaged to derive estimates of e.g. yield, moisture content, percent loss, establishment failure rate, N input rate, etc. representative of best practices. A thorough data analysis, including 2013's data, will be performed by the OSCIA by the end of year 2013 to elaborate best practices and guidelines. Meanwhile, in the context of this LCA study, the OSCIA and the OFA provided their expertise and support to draw out best representative average required for the goal and scope of this study.

Data sources also included standard data relative to generic switchgrass and miscanthus studied elsewhere (e.g. in the U.S.A.) and to the general rules and practices in the field of their production in Canada and North America.

Missing, incomplete or non-accessible data were completed by **secondary data**, i.e. the life cycle inventory database *ecoinvent*, our own internal database, which includes data from over 10 years of LCA activity, dataset from public available databases, literature review and expert judgment. Most of secondary data came from the life cycle inventory (LCI) modules available in the European *ecoinvent* database 2.2 (www.ecoinvent.org). It is the most complete LCI database available and largely surpasses other commercial databases from a quantitative (number of included processes) and qualitative (quality of the validation processes, data completeness, etc.) perspective and is internationally recognized by experts in the field of LCA. It should be noted that using European data to represent Canadian processes can introduce some bias in certain areas. However, it is believed that the consistency and accuracy of this database make it a preferable option for representing Canadian conditions compared to other available data for most processes.

Whenever possible, generic datasets used in this study were adapted to increase their representativeness of the geographical context of the systems. More specifically, for all activities taking place in Ontario, the generic datasets were adapted by replacing the original electricity grid mixes (European) by:

- the Ontario grid mix for all foreground processes, when relevant;
- the Ontario grid mix and the supply of natural gas from Alberta for the production of urea fertilizer, which has been assumed produced in Ontario;
- The North American grid mix for all other background processes, i.e. all processes directly or indirectly linked to the foreground processes (e.g. diesel production). The North American grid mix was selected here considering that supply and waste management activities may occur anywhere and most probably in North America.

Therefore, all foreground processes taking place in Ontario (including transports) refer to background processes adapted to the North American energetic context.

Also, all data used have been:

1) Checked regarding their temporal, geographical and technological representativeness;
2) Collected at the highest level of detail possible;
3) Documented according to the best practices available.

When no source was available, assumptions were used in agreement with the OFA, with the support of the OSCIA (OSCIA/OFA, 2013). Table 3-2 (for switchgrass) and Table 3-3 (for miscanthus) present the processes that were included in the system boundaries and the main data sources and assumptions used in this carbon footprint study with respect to production activities. Details regarding field direct emissions and machinery modelling is presented in the following paragraphs. Also, all data used will be presented in detail in Appendix C.

Table 3-2 : Main data, sources and assumptions to build LCI of Switchgrass foreground system

Parameters	Amount	Possible range	Sources	Comments
Land preparation				
Chemical burndown	Glyphosate 1.2 kg active ingredient/ha		Kalita (2012); Engbers (2012); Eggimann (2013)	
Spraying	Boom sprayer; 160 HP; 1 pass; 2.1 L/ha		Survey; Kalita (2012);	
Ploughing	Disk plough; 2.5 passes; 180 HP; 7 L/ha	2 to 3 passes; 120 to 225 HP	Survey; Kalita (2012);	
Packing	Packer; 1 pass; 125 HP; 2.5 L/ha	1 pass; 100 to 150 HP	Survey; Kalita (2012);	
Seeding				
Seeds	12.3 kg/ha	7.8-13.5 kg/ha, most likely 11.2-13.5 kg/ha	Engbers (2012); Eggimann (2013)	Proxy for modeling seeds production: ecoinvent process “Grass seed IP, at regional storehouse/CH”
Sowing	Presswheel drill; 1 pass; 160 HP; 2.8 L/ha	150 to 160 HP	Survey; Kalita (2012);	
Packing	Packer; 1 pass; 125 HP; 2.5 L/ha	1 pass; 80 to 150 HP	Survey; Kalita (2012);	
Establishment failure rate (first establishment year)	25%	*Tested in sensitivity analyses from 0% to 90%*		Failure implies reseeding, hence additional seeds and operations for seeding, packing, herbicides application (including additional herbicide use) during the first establishment year. However, it also implies reduced operations for baling and further bales handling during the first year.
Weed control				
Weed management	Either mechanical (2 mowing/year) or chemical (2,4-D at 1 kg a.i./ha and atrazine at 1.1 kg a.i./ha). Management is modelled as 50% mechanical and 50% chemical		Engbers (2012); Eggimann (2013); Kalita (2012)	Only during first and second year of establishment. Switchgrass will ultimately shade out most weeds in 3rd year and later.
Spraying	Boom sprayer; 125 HP; 1 pass; 2.1 L/ha	80 to 160 HP	Survey; Kalita (2012);	
Mowing/Clipping	Rotary mower; 160 HP; 1 pass; 5.1 L/ha		Survey; ecoinvent database (Nemecek and Kägi, 2007)	
Fertilization				

Parameters	Amount	Possible range	Sources	Comments
Phosphate and Potassium fertilization	0	0 to an adjustment rate depending on local soil tests. OMAFRA (2009) suggest removal rates of 1.8 kg P2O5/t biomass harvested and 1.3 kg K2O/t (4 lbs and 2.9 lbs, resp.)	OSCIA/OFA (2013)	No P and K adjustment prior planting is considered. So far, Ontario producers' experience has shown that the overwintering of cut biomass allows maintaining P and K levels in soil during main productive phase.
Nitrogen fertilization	60 kg N/ha Urea	From 0 to over 100 kg N/ha. Also a general guideline/recommendation in Ontario is to add 20 lbs N/acre for each dry tonne of biomass harvested per acre (Eggimann, 2013). *Tested in sensitivity analyses*	OSCIA/OFA (2013)	From second year onwards. Rate depends on several factors like soil fertility, location, previous crop, cover cropping.
Fertilizer application	Broadcaster; 1 pass; 100 HP; 2.3 L/ha		Kalita (2012)	
Harvest				
Harvesting principle	Fall cutting (after first frost), overwintering in windrows, and harvesting in Spring (April-May) the next year	Recommended method	OSCIA/OFA (2013)	Allows nutrient leaching during overwintering (nutrient return to soil, and better quality biomass for combustion) but a much lower yield.
Yield (main productive phase)	8650 kg/ha	7400-9900 kg/ha (3-4 tonne/acre) *Tested in sensitivity analyses*	Eggimann (2013)	Much variable
Yield during first and second establishment years	First year: 10% of main productive phase yield; Second year: 50%		Eggimann (2013)	Much variable. As main yield, it depends on land fertility and marginality, weed control efficiency, etc. The figures accounts for failure of stand establishment.
Moisture of harvested biomass	10%	8-12%	Eggimann (2013)	
Swathing	Rotary windrower; 160 HP; 7.8 L/ha		Kalita (2012)	Haybine (e.g. with 120 HP tractor) is reported by some producers surveyed as very challenging for full grown switchgrass
Raking	Swath turner; 70 HP; 4.3 L/ha	70 to 85 HP	Kalita (2012); survey	
Baling	Large size baler; 1 pass; 250 HP; 17.6 L/ha	200 to 250 HP	NETL (2010); Kalita (2012); survey	
Bale dimensions	Large rectangular bale 1.2*0.9*2.4 m (W x H x L) *(4*3*8 feet)*	round bale to smaller size rectangular bale		Size and density of bale depend on foreseen market and transportation distance

Parameters	Amount	Possible range	Sources	Comments
Bale density	200 kg/m^3	Varies greatly : 200-220 kg/m3 can be achieved with newer technology, versus the normal 160-180 range achieved with traditional large bale technology (REAP, 2008); 210-255 for mid and large square bale of generic biomass (OMAFRA, 2011)		Size and density of bale depend on foreseen market and transportation distance
Twine for bale	Polypropylene twine 0.355 kg/bale	Data from several manufacturers and resellers give a twine consumption per bale that varies from 0.281 up to 0.385 kg twine, depending on bale length.	Krone North-America; http://agritools.cordex.com; ipstretch.com	Polypropylene (PP): PP is extruded, fibrillated, and yarned onto spools. Virgin PP is considered (source: Krone North-America)
Bale loading	Loader; 0.097 L/bale		ecoinvent database (Nemecek and Kägi, 2007)	
Bale transport from field to farm yard	Tractor and trailor; 0.0522 L/t.km; distance: 4 km assumed	*Transport vs. bales on the field tested in sensitivity analyses*	ecoinvent database (Nemecek and Kägi, 2007)	
Other				
Stand lifetime	15 years (including the 2 establishment years)	10-20 years *Tested in sensitivity analyses*	OSCIA/OFA (2013)	No stand deterioration is considered with time which could lead to a reduced yield with time in late years
Transportation distance for supplies	80 km distance from storehouse to farm (seeds: 200 km); pick-up/van <3.5t assumed (consumption: 0.472 L/tonne.km)		OSCIA/OFA (2013)	For fertilizers, pesticides, bale twines, seeds.
Transportation of people	9.6 L/ha for year 1 1.4 L/ha for year ≥2		Survey (one miscanthus producer)	Field visits by farmer. Assumed applicable to the switchgrass system

Table 3-3 : Main data, sources and assumptions to build LCI of Miscanthus foreground system

Parameters	Amount	Possible range	Sources	Comments
Land preparation				
Chemical burndown	Glyphosate 1.2 kg active ingredient/ha		Kalita (2012); Engbers (2012)	Same rate as for switchgrass is considered
Spraying	Boom sprayer; 80 HP; 1 pass; 2.2 L/ha	25 to 80 HP	Survey	
Ploughing	Disk plough; 2,5 passes; 120 HP; 8,5 L/ha	Furrow plow 75 HP + field cultivator 75 HP + rototiller 75 HP; tandem disc 120 HP + rototiller 35 HP	Survey	
Packing	Packer; 1 pass; 125 HP; 2.5 L/ha	1 pass; 100 to 150 HP	Survey; Kalita (2012);	
Planting				
Rhizomes	21000/ha	12300 to 29600/ha	Engbers (2012)	This implies cultivating around 0.1 ha rhizomes per ha miscanthus since it is assumed that 1 ha supplied rhizomes to plant 10 ha at around 21 000 rhizomes/ha (Hamelin, 2011)
Planting	Transplant planter; 1 pass; 80 HP	75-80 HP	Survey	Modelled like a potato planter. ecoinvent database (Nemecek and Kägi, 2007)
Packing	Packer; 1 pass; 125 HP; 2.5 L/ha	1 pass; 80 to 150 HP	Survey	1 producer surveyed does pack; another one does not
Establishment failure rate (first establishment year)	10%	*Tested in sensitivity analyses from 0% to 90%*		Failure implies reseeding, hence additional seeds and operations for seeding, packing, herbicides application (including additional herbicide use) during the first establishment year. However, it also implies reduced operations for baling and further bales handling
Weed control				
Weed management	Either mechanical (2 mowing/year) or chemical (2,4-D at 1 kg a.i./ha and atrazine at 1.1 kg a.i./ha). Management is modelled as 50% mechanical and 50% chemical		Engbers (2012); Eggimann (2013); Kalita (2012)	Only during first and second year of establishment. Due to lack of information for miscanthus, the same pesticides and rates as for switchgrass are applied

Parameters	Amount	Possible range	Sources	Comments
Spraying	Boom sprayer; 80 HP; 2 pass; 2.2 L/ha	25 to 80 HP	Survey; Kalita (2012);	
Mowing/Clipping	Rotary mower; 160 HP; 1 pass; 5.1 L/ha		Survey; ecoinvent database (Nemecek and Kägi, 2007)	
Fertilization				
Phosphate and Potassium fertilization	0	0 to an adjustment rate depending on local soil tests.	OSCIA/OFA (2013)	No P and K adjustment prior planting is considered.
Nitrogen fertilization	60 kg N/ha Urea	From 0 to over 100 kg N/ha. Also a general guideline/recommendation in Ontario is to add 20 lbs N/acre for each dry tonne of biomass harvested per acre (Eggimann, 2013). *Tested in sensitivity analyses*	OSCIA/OFA (2013)	From second year onwards. Rate depends on several factors like soil fertility, location, previous crop, cover cropping.
Fertilizer application	Broadcaster; 1 pass; 80 HP; 2.3 L/ha		Survey	
Harvest				
Harvesting principle	Spring cutting and harvesting ; overwintering on stands	Practice used by all producers surveyed	OSCIA/OFA (2013); survey	Allows nutrient cycling back to root at dormancy, a lower moisture of harvested biomass and better quality biomass for combustion), but a much lower yield.
Yield (main productive phase)	13590 kg/ha (5.5 t/ac)	5600-21400 kg/ha *Tested in sensitivity analyses*	Engbers (2012); survey	Varies greatly
Yield during first and second establishment years	First year: 0% of main productive phase yield; Second year: 50%	For year 2: 0.35-0.7	survey	Varies greatly. As main yield, it depends on land fertility and marginality, weed control efficiency, etc. The figures accounts for failure of stand establishment.
Moisture of harvested biomass	13%	7-17%	Engbers (2012); survey	
Cutting	Rotary mower; 160 HP; 7.8 L/ha		survey	Haybine tested on year 2 by one producer who switch to mower for year 3
Baling	Large size baler; 1 pass; 250 HP; 17.6 L/ha	150 to 250 HP	NETL (2010); survey	
Bale dimensions	Large rectangular bale 1.2*0.9*2.4 m (W x H x L) *(4*3*8 feet)*	round bale to smaller size rectangular bale		Size and density of bale depend on foreseen market and transportation distance

Parameters	Amount	Possible range	Sources	Comments
Bale density	200 kg/m^3	Varies greatly : 200-220 kg/m3 can be achieved with newer technology, versus the normal 160-180 range achieved with traditional large bale technology (REAP, 2008); 210-255 for mid and large square bale of generic biomass (OMAFRA, 2011)		Size and density of bale depend on foreseen market and transportation distance
Twine for bale	Polypropylene twine 0.355 kg/bale	Data from several manufacturers and resellers give a twine consumption per bale that varies from 0.281 up to 0.385 kg twine, depending on bale length.	Krone North-America; http://agritools.cordex.com; ipstretch.com	Polypropylene (PP): PP is extruded, fibrillated, and yarned onto spools. Virgin PP is considered (source: Krone North-America)
Bale loading	Loader; 0.097 L/bale		ecoinvent database (Nemecek and Kägi, 2007)	
Bale transport from field to farm yard	Tractor and trailor; 0.0522 L/t.km; distance: 4 km assumed	*Transport vs. bales on the field tested in sensitivity analyses*	ecoinvent database (Nemecek and Kägi, 2007)	Tractor and wagon used by on producer surveyed
Other				
Stand lifetime	15 years (including the 2 establishment years)	10-20 years *Tested in sensitivity analyses*	OSCIA/OFA (2013)	No stand deterioration is considered with time which could lead to a reduced yield with time in late years
Transportation distance for supplies	80 km distance from storehouse to farm (200 km for rhizomes); pick-up/van <3.5t assumed (consumption: 0.472 L/tonne.km)		OSCIA/OFA (2013)	For fertilizers, pesticides, bale twines, and rhizomes
Transportation of people	9.6 L/ha for year 1 1.4 L/ha for year ≥2		Survey (one producer)	Field visits by farmer, servicing. Data from one switchgrass producer used as proxy

3.6.1 Direct field emissions

Direct field GHG emissions considered include nitrous oxide (N_2O) as well as CO_2 emissions from land use and land use change. GHG emissions from fuel combustion are presented later. No methane emission has been considered since it is considered negligible in this cropping context (e.g. no livestock implication, no land use change from wetland).

Nitrous oxide (N2O) air emissions

Nitrogen (N) inputs leads to N_2O air emissions through direct and indirect pathways (through nitrate leaching and runoff and ammonia volatilization and redeposition) and contribute to global warming. Emission rates vary based on the soil characteristics, climatic conditions and agricultural practices. N_2O air emission was calculated based on the methodology developed by Rochette *et al.* (2008), which is a Tier II contextualization of IPCC methodology (IPCC, 2006) used for reporting national GHG inventory (Environment Canada, 2008). The Tier II methodology for Canada estimates direct soil emissions at finer spatial and temporal scales than the IPCC default using baseline regional emission-factor relationships derived from the N application rate, the ratio of precipitation to potential evapotranspiration, topographic landscape positions, soil texture, and management practices. Furthermore, it implicitly accounts for spring-thaw N2O emissions for eastern regions.

For this LCA study, regional emission factors for Ontario were specifically averaged for the ecoregions 5E, 6E and 7E (presented in Section 3.2) from individual ecodistrict-level emission factors available within Holos tool (Little *et al.*, 2008, 2013). They are presented in Table 3-4. N inputs considered throughout the study are:

- N brought by urea application (N content 46%);
- N from above-ground crop residues (litter – or un-harvested cut biomass – and stubble) and from below-ground residues (root system);
- N inputs from mineralization of native soil organic matter as a consequence of land use change;

In the reference scenario, it is assumed that all nitrogen from yearly-generated above-ground residues is made available for entering the processes of N transformation (volatilization, leaching and run-off, nitrification/denitrification) leading to direct and indirect N_2O emissions. The same is also assumed for the below-ground vegetation, i.e. the root system, but only once in the lifetime of the cropping system. In other words, the root system is considered as a steady-state living mass, which N is prorated over its lifetime to simulate an annual turn-over. **Note however that a reduced mass of the root system is considered in the calculations for the establishment years 1 and 2 as compared to the productive years, to the same extent the yield is reduced in the two first years**. The same logic is applied for above-ground residues.

In addition to these inputs, the influence of soil texture and tillage level on N_2O emission from N inputs are also accounted for as additional emissions, according to the Canadian methodology (Rochette *et al.* 2008). The value of the ratio factors RF*x* used is presented in Table 3-4. Each of these two N_2O emissions is factored as follow from direct N_2O emissions from N inputs:

$$N_2O\text{-}N_{\text{soil texture or tillage level}} = N_2O\text{-}N_{\text{inputs}} * (RFx - 1)$$

N_2O emission due to position in landscape/topography is an additional source of N_2O of the Canadian methodology (Rochette *et al.* 2008). However, this source has not been considered here due to the large variability of the ratio factor within the ecodistricts (mean: 10.05; Standard deviation: 7.34), and of the questionable large contribution - around 65% - this single source shows on total N_2O per ha and per year of preliminary calculations.

Table 3-6 presents the nitrogen concentration of biomass components that have been used in the calculations of N inputs from crop residues.

Table 3-4 : Emission factors and parameters for nitrous oxide emissions from input

Emission	Parameter	Value	Source
N_2O Direct	EF eco average (kg N_2O-N/kg N input)	0.01426	Rochette et al. (2008); Little et al. (2013). Special Ontario average
N_2O Indirect, through leaching	Leaching fraction (-) *Fraction of N inputs leached as NO3-N*	0.25678	Rochette et al. (2008); Little et al. (2013). Special Ontario average
	EF leaching (kg N_2O-N/kg N leached)	0.0075	IPCC (2006)
N_2O Indirect, through volatilization *(applies only to fertilizer N inputs)*	Volatilization fraction (-) *Fraction of N inputs volatilized as NH3-N and redeposited*	0.1	IPCC (2006)
	EF volatilization (kg N_2O-N/kg N volatilized)	0.01	IPCC (2006)
N_2O from soil texture	Ratio factor for soil texture, RFtext (-) Considering *"Reduced & No-till"* tillage level and a *"medium"* soil texture.	0.8	Rochette et al. (2008); Little et al. (2013).
N_2O from tillage level	Ratio factor for soil texture, RFtill (-) Considering *"Reduced & No-till"* tillage level and a *"medium"* soil texture.	1.1	Rochette et al. (2008); Little et al. (2013).

Carbon dioxide (CO_2) emissions from land use and land use change

Land use change (land transformation)

Organic C is stored in three different pools: the below-ground biomass (root system), the un-harvested above-ground biomass (stubble and litter), and the soil. When changing land utilization, these storage pools can change until a new equilibrium is reached. The harvested biomass is not accounted for since it is removed every year and does not participate to change in the above-ground pool. Especially because of their developed root system, cropping perennials like Switchgrass and Miscanthus is reported to sequester C, which occurs when the inputs of C are greater than removals from decomposition. Kludze (2011) mentions values from the literature of 0.7 and 0.5 tonne C/ha.year in Ireland and UK respectively for Miscanthus; and rates of 0 tonne C/ha.year for soil (changed from cropland) and of 1.7-2.1 as root biomass inputs in the US for Switchgrass, and also of 0 tonne C/ha.year for Switchgrass cropped without manure input on a previous abandoned land in Quebec. Cherubini and Jungmeier (2010) use an average of 0.6 tonne C/ha.year from a range of 0.2-1.1 tonne C/ha.year (from the literature) for soil sequestration rate for Switchgrass in their LCA. The rate of C sequestration depends on land-use history, soil type, plant type, harvesting cycle, and other management practices. In their meta-analysis[2], Anderson-Texeira et al. (2009) could hardly derive a significant and robust trend with respect to SOC change for Miscanthus, even

[2] Assembly and analysis of published estimates of SOC change following conversion of natural or agricultural land to biofuel crops of corn with residue harvest, sugarcane, Miscanthus x giganteus, switchgrass, or restored prairie.

though results suggest an initial soil C loss after land transformation, followed by an accumulation at a rate averaging 1 tonne C/ha.year. Accumulation rate for Switchgrass statistically averaged between 0.4 and 0.7 tonne C/ha.year. Lastly, Mishra et al. (2013) have estimated that cultivating Miscanthus would result in a SOC sequestration at the rate of 0.16–0.82 tonne C/ha.year across the U.S. croplands due to cessation of tillage and increased biomass carbon input into the soil system. Long-term studies are still too few to provide accurate and robust data that could be used with confidence to the Ontario context. Also, studies differ on the influence of soil depth measurement of soil carbon. Anderson-Texeira et al. (2009) observed no significant change of SOC change with depth (up to 60 cm) for Switchgrass and Miscanthus. Conversely, Follett et al. (2012) report results of a Switchgrass 9 years long-term C sequestration study in eastern Nebraska and emphasize the need to deep sample soil C up to 150 cm (over 50% of the change in soil C was below the 30 cm depth). The authors report an average increase in SOC of 2.1 tonne C/ha.year for Switchgrass cropped with management practices similar to the ones of our study (fertilization at 60 kg N/ha and late harvest after a killing frost). Finally, it should be noted that numerous studies reporting sequestration rates do not detail whether vegetation pool (and especially the below-ground root system) is also considered in addition to the soil pool.

This brief literature review demonstrates that there is a rather large (and consensual) uncertainty with respect to reference values for sequestration rates. In the absence of robust primary data (i.e. soil measurements) relative to the Ontario context, our study will first apply the IPCC guidelines and default data to derive estimates of C gain/loss from the soil and the vegetation pools. This is described in the following paragraphs. Then a sensitivity analysis will be performed with sequestration rates chosen within the range typically reported by the literature above-mentioned, i.e. [0-2 tonne C/ha.year].

Soil organic carbon

The previous land use types and managements to consider within the context of the study have been evaluated with the OFA (OSCIA/OFA, 2013) and are presented in Table 3-5.

Table 3-5 : Land use and land use management previous to biomass cropping in Ontario

Previous Land use and management	Miscanthus	Switchgrass
Cropland (corn-soybean-wheat rotation)	90%	75%
Pasture Management: No-till	5%	12.5%
Abandoned land	5%	12.5%

For cropland previous use, a mixed management is assumed based on 44% full-till, 25% reduced, and 31% no-till practices in Ontario as reported (through Statistics Canada, 2007). The resulting changes in soil organic carbon (SOC) from soils are calculated using the IPCC methodology and default factors (also in line with the European Commission’s Renewable Energy Directive (European Commission, 2010)) These are presented in Figure 3-4 (section 1.1 of the figure). Soil carbon change from land transformation for Switchgrass implies a loss of 4.5 tonne C/ha, whereas the loss is 3.1 tonne C/ha for Miscanthus. The loss is then allocated to the total biomass production over the useful lifetime considered, i.e. 15 years.

Annualized over the typical (but arbitrary) IPCC time horizon of 20 years, the loss rate is 0.23 and 0.16 tonne C/ha.year, respectively.

Carbon sequestration by vegetation

Table 3-6 presents the carbon concentration of biomass components that have been used in the calculations of C stocks changes in the vegetation. It has been assumed that the total mass of litter (leaves), stubble and below-ground biomass participates equally in C vegetation stock. Values of C in the vegetation of former land use have been calculated using IPPC methodology and default data (European Commission, 2010) and are presented in Figure 3-4 (section 1.2 of the figure). The change in C vegetation stock derived is 2.9 and 6 tonne C/ha for Switchgrass and Miscanthus, respectively.

Total soil and vegetation C stocks change due to land use change

For Switchgrass, the net change from the three pools of carbon results in a **loss of 1.6 tonne C/ha** (Figure 3-4 (section 1.3 of the figure). Conversely, for miscanthus, the net change is a **sequestration of 2.9 tonne C/ha**.

As mentioned, this CO_2 inventory results are based on the IPCC methodology and default data (except for the C vegetation stock of the two biomass crops). The difference between the two crops lies mainly in the extent of the below-ground vegetation C stock (5.22 tonne C/ha for Miscanthus *vs.* 3.46 for Switchgrass) as shown in Figure 3-4, section 1.2. Furthermore, the higher share of cropland as a previous land use for Miscanthus (90% vs. 75%) advantages Miscanthus since changing from cropland use to biomass land use minimizes soil C loss (Figure 3-4, section 1.2) compared to the two other land use change options. As a result, land use change for Miscanthus leads to a C gain (hence a CO_2 credit), whereas it leads to C loss for Switchgrass (hence a CO_2 emission) for which the increase in vegetation C stock does not offset soil C loss. It is worth noting that a slight change of IPCC factors induces a large change in estimates of C loss/gain (see Appendix F for a simulation across the whole range of available IPCC factors). This high sensitivity demonstrates the uncertainty that can be conveyed to the final carbon footprint when the CO_2 from soil, in absolute (i.e. whether a credit or an emission), is a high contributor to the footprint.

Table 3-6 : Mass balance and carbon and nitrogen concentration of biomass components

	Above-ground biomass (AG)									Below-ground biomass (BG)						Source
	AG harvested			AG stubble (10 cm)			AG harvest litter (field loss)			BG AP-Horizon Roots			BG B-Horizon Roots			
	%C	%N	% dry mass (AG+BG)	%C	%N	% dry mass (AG+BG)	%C	%N	% dry mass (AG+BG)	%C	%N	% dry mass (AG+BG)	%C	%N	% dry mass (AG+BG)	
SG Cave-in-Rock (Northwestern Pennsylvania)	44.5	0.63	38%	46	0.42	4%	42.5	0.86	11%	40.1	0.7	45%	36.9	0.45	1%	Gallagher et al. 2010
MS	45.7	0.5	40%	45.7	0.5	2%	45.7	0.5	10%	41	0.9	36%	41	0.6	12%	Dohleman et al. 2012 + own assumtions

Notes: Switchgrass AG harvest litter represents 28% of harvested material, which is in line with the loss percent reported by surveyed producers (range of 25-30%) ; Miscanthus stubble mass % are estimated as 10 cm of 180 cm stand height. See Appendix C for more details about calculations; Dohleman et al. values (2012) are taken as of December (complete dry down) monthly average figures, and BG are made of rhizome and roots (up to 100 cm depth).

3.6.2 Machinery modelling

The data for material consumption related to the different tillage operations and fieldwork were taken from the *ecoinvent* database (v2.2), but the diesel consumption was adjusted based on data collected from the producers surveyed (two Switchgrass producers and two Miscanthus producers) and also already collected by Kalita (2012) from an Ontario switchgrass producer. The data from the *ecoinvent* database include the machinery production, repair and maintenance (including oil consumption and the management of waste oil), shed for tractor and machinery, etc. All processes are described in Nemecek and Kägi (2007). The process used from the *ecoinvent* database estimate many of the emissions to air based on the diesel consumed. These were corrected accordingly.

3.6.3 Life cycle inventory modeling and calculations

A combination of Microsoft Excel® and SimaPro 7.3.3 software, developed by PRé Consultants (www.pre-sustainability.com), was used to assist the LCA system modeling, link the reference flows with the life cycle inventory database and compute the complete life cycle inventory of the systems.

1 - IPCC and EU's RED directive methodology for soil and vegetation carbon stocks change due to land use change

1.1 - Soil Organic Carbon change from land use change according to IPCC methodology (applies also to EU's RED and RSB methodology)

For European Directive (based on IPCC), see: COMMISSION DECISION of 10 June 2010 on guidelines for the calculation of land carbon stocks for http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:151:0019:0041:EN:PDF

For RSB methodology, see: http://rsb.org/pdfs/12-12-20-RSB-STD-01-003-01-RSB-GHG-Calculation-Methodology-v2-1.pdf

Factors F taken using the IPCC Tool (downloaded from IPCC website)

Climate region	Canada; Warm temperate, moist
Soil type	Low clay activity mineral
SOC(ST), standard SOC in the 0-30 cm topsoil layer (t C/ha)	63

Note: value in range of the ON standard SOC, which is much variable: 22-112 t C/ha (VandenBygaart et al. (2003). Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies. Can. J. Soil Sci. 83:363-380)

Case 1: Reference land use = cropland; mixed tillage practices

	Biomass land use		Reference land use (before change)	
Land use Factor (Flu)	Long-term cultivated	0,71	Long-term cultivated	0,71
Management Factor (Fmg)	50% Reduced-till, 50% No-till (1)	1,13	44% Full-till, 25% Reduced, 31% No-till (2)	1,07
Input Factor (Fi)	Low	0,91	Medium	1
SOC of the starting condition (year 0) (t C/ha)				48,0
Predicted SOC stock (t C/ha)		45,8		
Annual SOC change over 20 years (t C/ha.a)	-0,11			

Case 2: Reference land use = grassland; no till; no input

	Biomass land use		Reference land use (before change)	
Land use F(LU)	Long-term cultivated	0,71	Grassland	1
Management F(MG)	50% Reduced-till, 50% No-till (1)	1,13	Nominal/non degraded	1
Input F(I)	Low	0,91	N/A	1
SOC of the starting condition (year 0) (t C/ha)				63,0
Predicted SOC stock (t C/ha)		45,8		
Annual SOC change over 20 years (t C/ha.a)	-0,86			

Case 3: Reference land use = abandoned land

	Biomass land use		Reference land use (before change)	
Land use F(LU)	Long-term cultivated	0,71	Set-aside (<20years)	0,82
Management F(MG)	50% Reduced-till, 50% No-till (1)	1,125	N/A	1
Input F(I)	Low	0,91	N/A	1
SOC of the starting condition (year 0) (t C/ha)				51,7
Predicted SOC stock (t C/ha)		45,8		
Annual SOC change over 20 years (t C/ha.a)	-0,29			

	Weighted SOC of the starting condition (at year 0) (t C/ha)	Weighted annual SOC change over 20 years (t C/ha.a)	**Weighted SOC change (t C/ha)**	
Switchgrass	50,3	-0,23	-4,5	Starting conditions: 75% case 1 (cropland) ; 12,5% case 2 (grassland); 12,5% case 3 (abandoned land) (Source: OSCIA/OFA 2013)
Miscanthus	48,9	-0,16	-3,1	Starting conditions: 90% case 1 (cropland) ; 5% case 2 (grassland); 5% case 3 (abandoned land) (Source: OSCIA/OFA 2013)

(1) Because some producers are now considering direct seeding, and because productive years involve no tillage operations.
(2) Statistics Canada (2007). Selected Historical Data from the Census of Agriculture: Table 5.1. http://www.statcan.gc.ca/pub/16-002-x/2008003/article/10688-eng.htm

1.2 - Above ground (AG) and Below-ground (BG) vegetation carbon stocks change due to land use change according to IPCC methodology (applies also to EU's RED and RSB methodology)

The change in carbon stocks in biomass is calculated by subtracting the net carbon accumulation by the projected land use from the carbon stored in the land use at the starting condition (at year 0)

		Switchgrass	**Miscanthus**	
Starting condition (year 0)	AG vegetation (t C/ha)	0,78	0,31	Weighing: For cropland=0; For grassland=1,27 (in warm temperate-wet climate zone); For set-aside (assuming scrubland)=5 (in temperate, global). Source: European Commission, 2010
	BG vegetation (t C/ha)	0,94	0,38	Weighing: For cropland=0; For grassland=5,53 (in warm temperate-wet climate zone); For set-aside (assuming scrubland)=2 (in temperate, global). Source: European Commission, 2010
Changed condition	AG vegetation (t C/ha)	1,21	1,46	Calculated from biomass components yield and content
	BG vegetation (t C/ha)	3,46	5,22	Calculated from biomass components yield and content
Change	AG+BG vegetation (t C/ha)	2,95	5,99	

1.3 - Total: soil C + AG and BG vegetation C stocks change due to land use change according to IPCC methodology (applies also to EU's RED and RSB methodology)3

	Switchgrass	**Miscanthus**
Net change in C stocks from land use change (t C/ha)	-1,6	2,9
as kg C/kg dm biomass harvested	-0,015	0,018
as kg CO2/kg dm biomass harvested	-0,054	0,066

A negative value means a net C loss (hence CO2 emission); a positive value means a C sequestration

Figure 3-4 : Calculations of soil and vegetation carbon change for Switchgrass and Miscanthus using the IPCC methodology and default factors for land use type, land management type and input level type.

3.7 Climate change impact assessment method and indicator

The impact assessment related to GHG emissions has been carried out using the “IPCC 2007” method. The Intergovernmental Panel on Climate Change (IPCC) method was chosen because it considers a global warming potential over a 100 years, which corresponds to the most common temporal horizon in GHG accounting. It accounts for the global warming potential of each GHG based on the model of the IPCC in kilograms of carbon dioxide equivalent (kg CO_2 eq.) based on infrared radiative forcing. The GHG potentials are estimated over a 100-year time horizon.

It is worth noting that the biogenic CO_2 emitted from plant respiration is usually not considered as contributing to climate change (i.e., its GWP=0) because it participates in a short carbon cycle, unlike the CO_2 from fossil fuel combustion. This biogenic CO_2 results from CO_2 captured from air during plant photosynthesis and is re-emitted shortly to the atmosphere. By extension, the CO_2 emitted during biomass decomposition or combustion is also considered having a GWP=0 because of its biogenic origin. Similarly, biogenic CO emissions from biomass combustion are also not accounted for by the “IPCC 2007” method. Furthermore, the GWP of biogenic methane (generated during the anaerobic decomposition of biomass) has been adjusted to account for the part of it that comes from initial CO_2 capture during biomass growth. The GWP of biogenic methane is thus 22 instead of 25 kg CO_2 eq./kg biogenic CH_4.

It is important to mention that life cycle impact assessment results present potential and not effective environmental impacts. They are relative expressions (to the functional unit namely) which do not predict the final impact or risk on the natural media, exceeding standards or safety margins.
A second impact assessment based on the “GHG Protocol” method allowed verifying if the variability of some GWP had a significant influence on the conclusions, and therefore to test the results robustness obtained with the “IPCC 2007” method.

As for the life cycle inventory, the SimaPro 7.3.3 software was used to calculate the impact scores associated with the emission inventory.

3.8 Interpretation

This last phase of the LCA aims to discuss the impact results obtained and to put them in perspective.

Given the objective of the study and its target audience, the discussion of the results is presented in Chapter 4 in simplified terms. However, the conclusions are based on a complete and in-depth analysis of the inventory data and the LCIA. This includes, specifically:

- Data quality assessment and contribution analysis;
- Consistency and completeness analysis;
- Sensitivity and scenario analyses;
- Uncertainty analyses.

The methodology used for data analysis and interpretation, such as data quality assessment, consistency and completeness checks, sensitivity analyses and the uncertainty analyses are summarized here. But first, a clarification is provided concerning the inventory analysis.

3.8.1 Inventory analysis

Inventory results in terms of quantities of material and energy associated to each system under study are not presented in the body of the report. Generally, a comprehensive analysis of inputs and outputs does not serve the understanding of issues involved. Indeed, inventory results usually convey much information, which does not directly allow any conclusions to be formulated. However, an inventory analysis is typically more effective when performed in parallel with impact assessment. Hence, the subsequent LCIA phase presented in Chapter 4 is actually an interpretation of LCI results and of their significance on the environmental damages, which is in agreement with ISO 14 044 standards. Also, the contribution analysis allows identifying those inventory flows that cause most of the impact within each impact category.

3.8.2 Data quality analysis

The reliability of the results and conclusions of the LCA depend on the quality of the study's inventory data. It is therefore important to ensure that the information meets certain requirements that are in line with the objectives of the study.
Though ISO does not propose a particular method, two criteria that impact inventory quality were selected to assess the data:

- **Reliability**: Pertains to the data sources, acquisition methods and verification methods. Reliable data has been verified and measured in the field. The criterion chiefly refers to flow quantification.
- **Representativeness**: Assesses the geographic and technological correlations. Does all of the data reflect reality? Data is representative when the technology is directly related to the field. This criterion chiefly refers to the choice of processes used when modeling the system.

A detailed description of the scoring system and the data quality assessment results are included in Appendix D.
Parallel to the data quality assessment, an estimation of the processes contribution (i.e. to what extent the process modeled with these data contributes to the overall impact of the system under study) was performed. Lower quality data may be very appropriate in the case of a process whose contribution is minimal. On the contrary, quality data should be collected for processes having a great influence on the conclusions of the study.
In this study, the contribution analysis simply consisted in the observation of the relative importance of the different processes to the overall climate change impact.

3.8.3 Sensitivity analyses

Several parameters used when modeling the systems present a certain degree of uncertainty, especially with regards to the generic data assumptions and modules and methodological choices. The results obtained relate to these parameters, and their uncertainty is transferred to the conclusions.

From the main contributors (processes/parameters) identified in the data quality assessment, five sensitivity analyses were performed on the following parameters:

- Nitrogen fertilization rate
- Yield (main productive phase)
- The amount of above- and below-ground crop residues nitrogen to consider effectively returned to soil
- Stands' lifetime
- The soil carbon sequestration rate

To do so, the values of selected uncertain parameters were switched for different but reasonable values. The extent of the variation in the results indicates the importance of the modified parameters on the global conclusions and the range in which the most valid results probably lie. Sensitivity analyses are presented in Section 4.3

Results have shown no significant sensitivity to the following parameters suspected of influence, both for switchgrass and miscanthus:

- *Stands' establishment failure rate*: Whereas the results are not affected for Switchgrass biomass (less than 0.2 % increase from a 10% failure rate (reference scenario) up to 90% failure), the Miscanthus carbon footprint is more sensitive to this parameter. From the 25% failure rate reference value, the footprint increases by 6% when failure is 75%, and decreases only by less than 3% for a 0% failure rate. The higher sensitivity for Miscanthus is mostly due to the higher burden from rhizome production and transport to farm compared to Switchgrass seeds.
- *The share between chemical and mechanical weed control*: the results are not affected within the range of 0% – 100% of one or the other way to control the weeds (less than +/- 0.1%).
- *The share between field storage and transport to farmyard (4 km) and storage in farm building of biomass bales :* here again, the result are not affected within the range of 0% – 100% of one or the other way to handle bales (0.7% maximum decrease when all bales are left on the field).

4 Results and discussion

4.1 Carbon footprint main results

Results are first presented without considering LUC change impact, i.e. the loss/gain of carbon from land use change, as well as emission of N_2O induced by the change when applicable. The reason is to display and to provide more details on the contributing steps that may be hindered by a high contribution of land use change. Results including LUC impact are presented in next section 4.2.

4.1.1 Switchgrass carbon footprint

Excluding land use change impact, the carbon footprint of Switchgrass is 0.152 kg CO_2eq/kg dry matter. Details of the contribution to the impact are presented in Figure 4-1. In fact, the productive phase (from year 3) is by far the main contributor to the footprint. Over 88% of the impact is due to this phase, whereas about 6% and 3% come from the establishment year 2 and 1, respectively, and 3% from the end-of-life of the root system (as N_2O emission). This is due to the fact that 95% of lifetime production arises during the 13 years of the productive phase.

Figure 4-2 reveals that 63% of the impact from this phase is due to direct soil emissions, broken down in 86% N_2O from N inputs (urea fertilizer and above-ground crop residues) and 14% CO_2 released from urea. Urea production and supply account for over 18% of the impact. The third contributor in importance is the baling operations, which life cycle GHG emissions (including direct GHG from diesel combustion) account for 10% of the productive phase's impact.

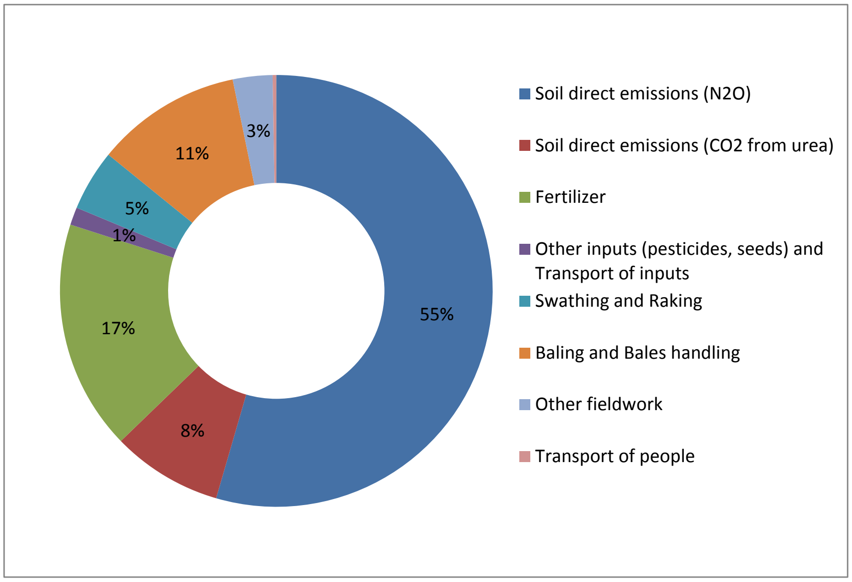

Figure 4-1 : Switchgrass carbon footprint: process contribution (excluding CO_2 from land use change).

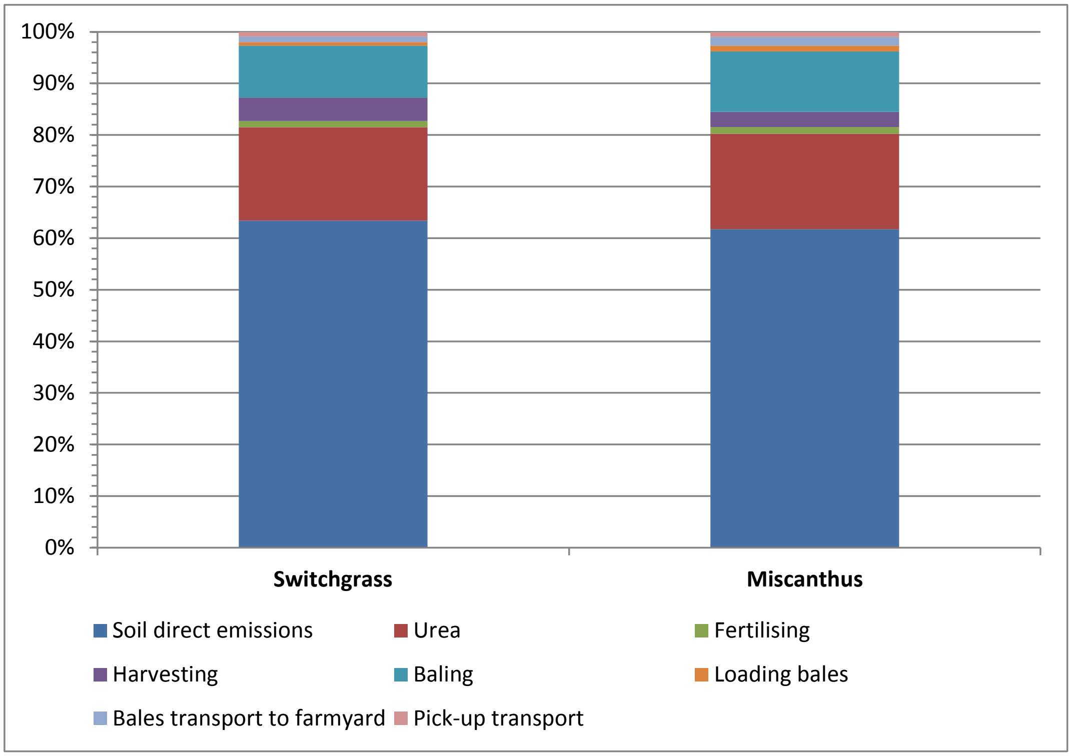

Figure 4-2 : Contributing processes of the main productive phase (years 3-15) for Switchgrass and Miscanthus.

4.1.2 Miscanthus carbon footprint

A rather similar result is obtained for Miscanthus in terms of process contribution (Figure 4-3). The carbon footprint is 31% lower, down to 0.104 kg CO_2eq/kg dry matter when land use change consideration is excluded. The higher dry matter yield, a reduced intensity for harvesting (no raking) and the slightly lower N input from yearly above-ground residues decomposition (17.7 kg N/ha vs. 22.5 for Switchgrass) contribute to a lower impact for Miscanthus. Also, "only" 83% of the impact comes from the main productive phase (vs. 88% for Switchgrass) for two main reasons. First, year 1 contributes for 6% (vs. 3% only for Switchgrass) because of the higher burden from rhizomes production, rhizome delivery at farm (due to higher weight) and planting than for Switchgrass seeds[3]. Second, the soil N_2O emission from the end-of-life of the Miscanthus below-ground vegetation contributes for 5% (vs. 3% only for Switchgrass) because of the larger mass of the Miscanthus root system. The latter provides almost twice as much N per ha than Switchgrass root system (116 vs. 66 kg N/ha) at end-of-life. Lastly, process contribution of the productive phase (
Figure 4-2) is very similar to Switchgrass, with soil emissions, urea production, and baling and bale handling operation as the three main contributors.

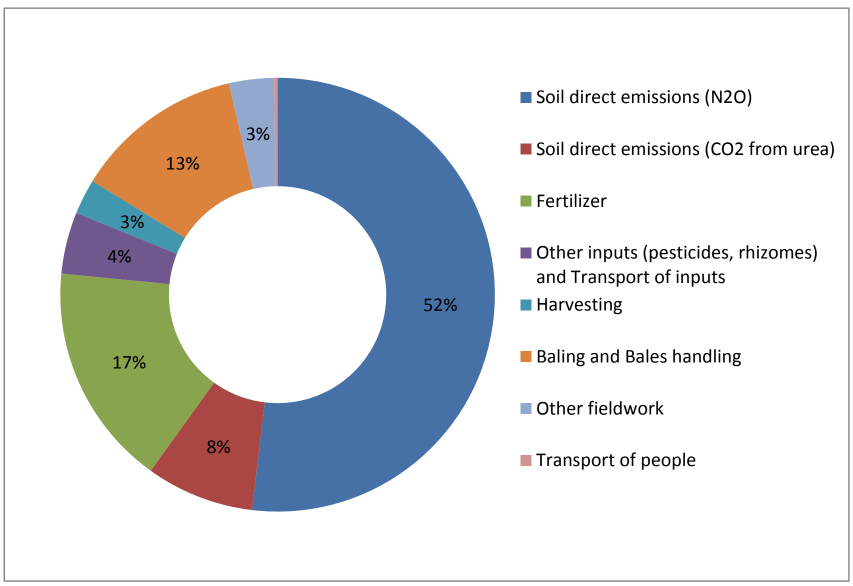

Figure 4-3 : Miscanthus carbon footprint: process contribution (excluding CO_2 from land use change).

[3] Note that Switchgrass seeds production has been proxied with *ecoinvent* database process "Grass seed IP, at regional storehouse" whereas rhizome production for planting has been entirely modelled from Miscanthus cultivation considering a 3 years production (year 1 to 3) without biomass harvesting.

4.2 Carbon footprint results including land use change and C sequestration

Figure 4-4 presents the previous results, now including the estimates of CO_2 emission/sequestration from land use change (soil stock and above- and below-ground vegetation stocks), in addition to N_2O emissions as a consequence of native soil organic matter mineralization (i.e. when SOC stock also decreases). Results are for the reference scenario based on the IPCC methodology for estimating soil C stock change, leading to a net loss of 1.6 tonne C/ha for Switchgrass from the three pools and to a sequestration of 2.9 tonne C/ha for Miscanthus (as described in section 3.6.1). For Switchgrass, this translates, once allocated to the functional unit, into the emission of 0.054 kg CO_2 per kg dry matter of biomass harvested, considering the weighted average annual yield of 7 058 kg dry matter harvested/ha. Conversely, for Miscanthus, it translates into a credit of 0.066 kg CO_2 per kg dry matter of biomass harvested, considering the weighted average annual yield of 10 641 kg dry matter harvested/ha. Since there is a SOC decrease for both crops, an additional source of N_2O is also considered, which corresponds to 0.029 and to 0.013 kg CO_2eq per kg dry matter for Switchgrass and Miscanthus, respectively.

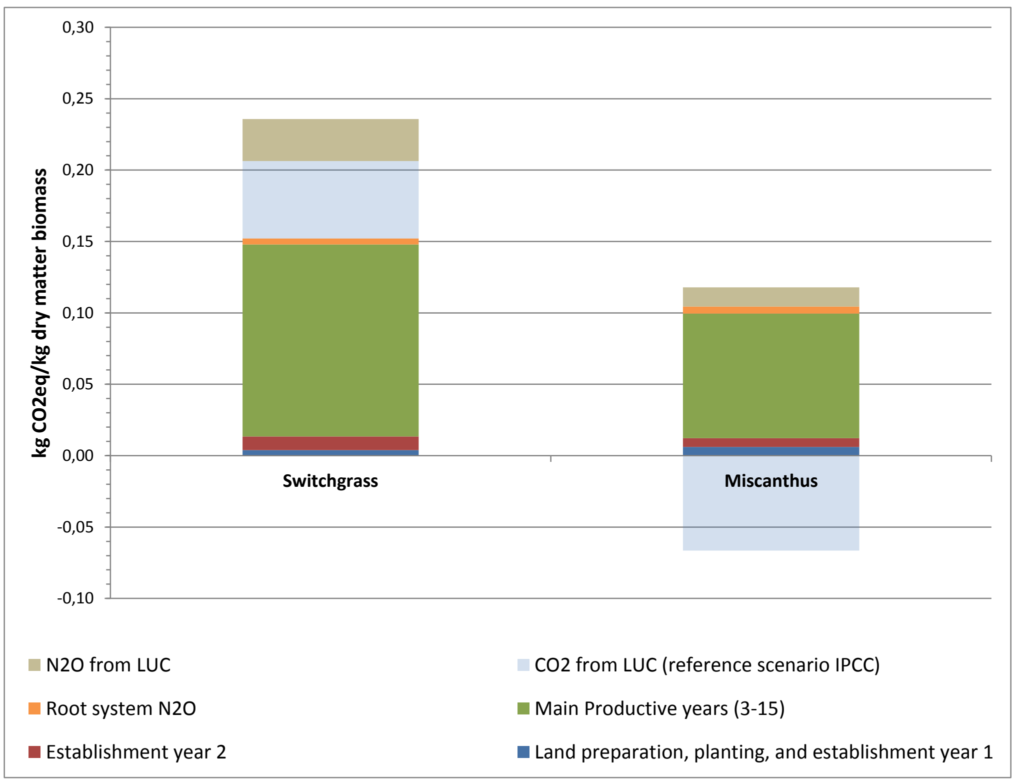

Figure 4-4 : Carbon footprint of 1 kg dry matter Switchgrass and Miscanthus, including net GHG from land use change.

As presented in Figure 4-4, the **Switchgrass** carbon footprint is estimated to **0.236 kg CO_2eq/kg dry matter**. Owing to the CO_2 credit, the **Miscanthus** scores **0.051 kg CO_2eq/kg dry matter**. Figure 4-5 displays the process contribution, with normalization to total emissions.

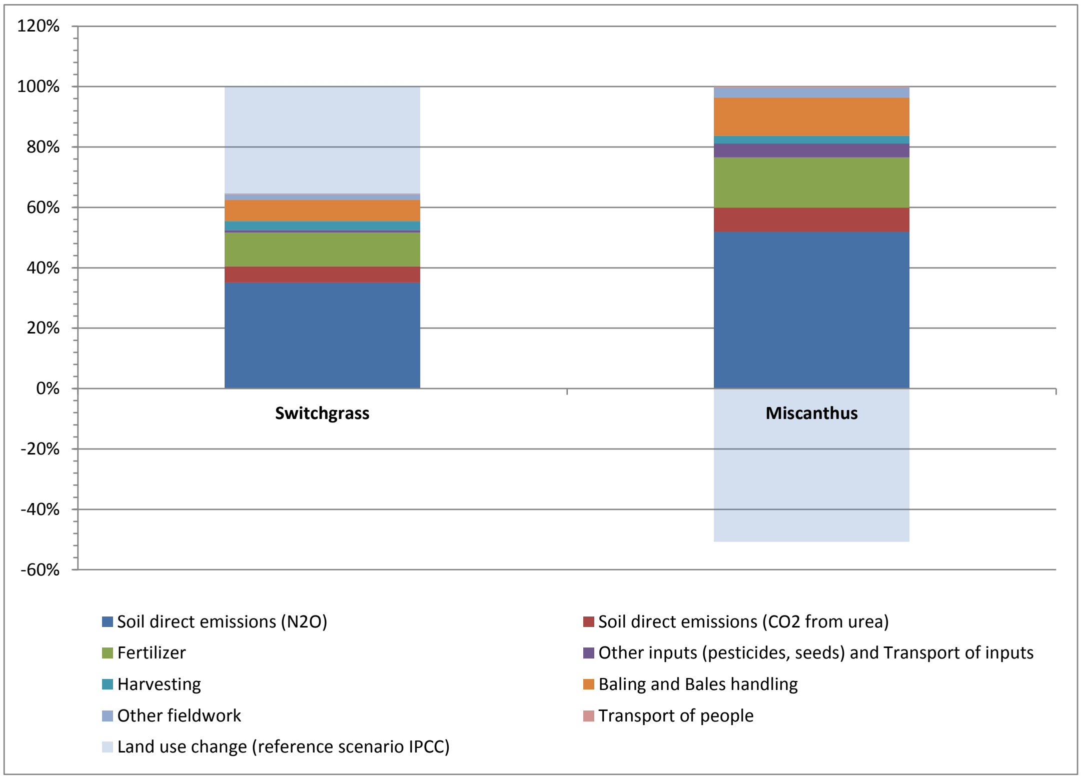

Figure 4-5 : Switchgrass and Miscanthus carbon footprint: process contribution (including net GHG from land use change).

4.3 Sensitivity analyses

The limitations of this preliminary analysis are mainly related to the incomplete and more or less valid inventory. Indeed, several processes originally included in the life cycle of the biomass systems studied have been estimated or averaged. The increase of the validity of certain processes in the inventory would surely modify the results of the analysis. It is therefore important to assess to what extent these changes could reverse the findings, especially if the estimated processes are different for the two systems and/or involve elements that seem to have the most influence on the results. Analyses are performed through changing one parameter while all others are maintained constant.
Also, the following scenario analyses below evaluate how a range of possible production parameters can affect the carbon footprint results, like the biomass yield or the fertilization rate.
Five sensitivity analyses have been performed to verify the influence of modeling assumptions on the conclusions of the study. Detailed tables are presented in Appendix E.

4.3.1 Sensitivity Analysis 1 – Fertilization rate

Fertilizer production and mineral nitrogen-induced soil emissions have already been identified as high contributors to the footprint for both biomass. Also, even though fertilizing at 60 kg N/ha is a recommended practice, future long-term biomass cropping experience might lead to the recommendation of lower rates without sacrificing the economic production. Conversely, increasing the level of input might become profitable if the biomass market can sustain a higher production cost. Furthermore, there may be variability between producers due to local climate and soil fertility. Figure 4-6 shows that the carbon footprint is significantly increasing with the fertilization rate. It should be reminded that all other model's parameters are constant throughout this simulation, especially the yield and all yield-based-characteristics such as above- and below-ground biomass components and their N and C contents (and subsequent emissions caused by these latter).

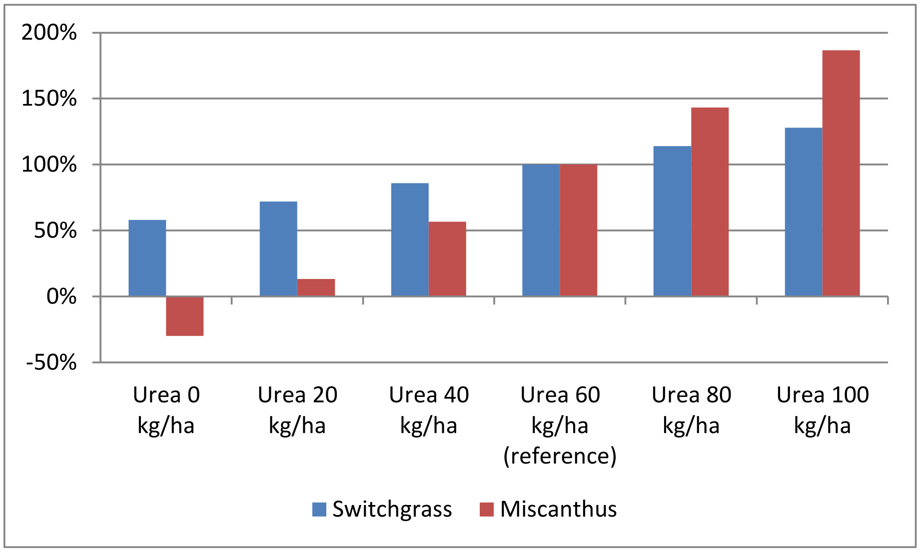

Figure 4-6 : Sensitivity of Switchgrass and Miscanthus carbon footprints to the fertilization rate.

Owing to its low carbon footprint thanks to the CO_2 credit from LUC, Miscanthus becomes carbon neutral at about 13 kg N/ha. Within the range of [0-100 kg N/ha], the carbon footprint of the Switchgrass remains positive, but can be almost two times lower without fertilization and 30% lower at 20 kg N/ha.

4.3.2 Sensitivity Analysis 2 – Amount of crop residues nitrogen effectively returned to soil

The reference scenario assumes that all nitrogen from yearly-generated above-ground residues is made available for entering the processes leading to direct and indirect N_2O emissions. The same is also assumed for the below-ground vegetation, i.e. the root system (see section 3.6.1). However, the biological reality is obviously more complex and a bioavailability of the nitrogen for these transformation processes might need to be considered. Furthermore, the seasonal cycles of nutrient allocation between above-ground biomass and the root system of such perennial crops (Heaton et al., 2009; Dohleman et al., 2012) add to the uncertainty of estimates of actual N_2O emission from crop residues.

The sensitivity analysis consisted in factoring the amount of crop residues nitrogen available for the above-mentioned processes of nitrogen transformation. Figure 4-7 presents carbon footprint results for the whole range of possibilities, although a reasonable range is likely within the 66% to 100% range.

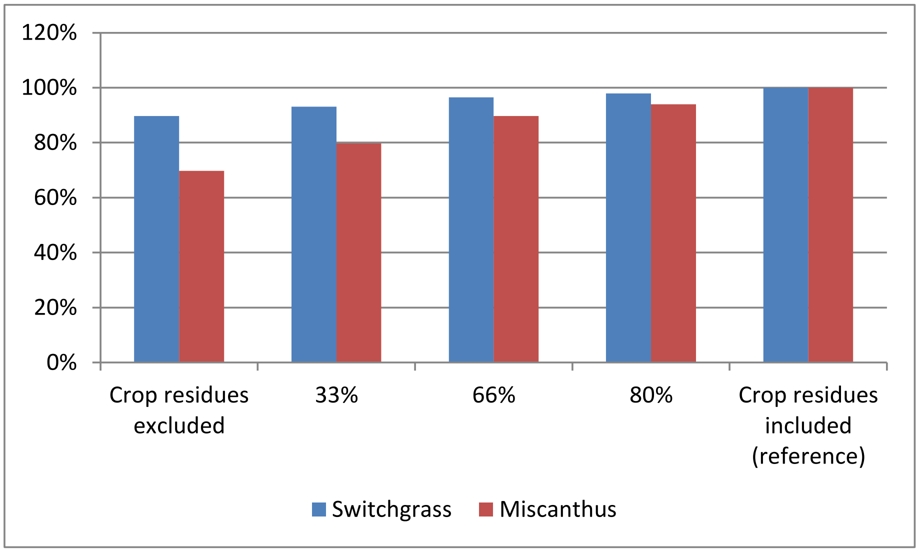

Figure 4-7 : Sensitivity of Switchgrass and Miscanthus carbon footprints based on the amount of crop residues nitrogen actually returned to the soil.

The Miscanthus carbon footprint is more sensitive to this parameter than Switchgrass. This is a consequence of the higher contribution of N_2O emission from crop residues for this crop as a result of the higher mass of crop residues. When 80% of the available nitrogen input is considered instead of 100%, the Switchgrass carbon footprint is down by about 2% (0.231 kg CO_2eq/kgharvested) and Miscanthus by 6% (0.048 kg CO_2eq/kg dry matter). At 66%, the decrease is by 4% and 10% for Switchgrass and Miscanthus carbon footprint, respectively.

4.3.3 Sensitivity Analysis 3 – Yield

The range of yield evaluated is the one observed from various producers trials (Engbers, 2012), which is very variable (see Table 3-2 and Table 3-3). Switchgrass yield is varied from 6 000 to 12 000 kg/ha on a humid basis (reference yield is 8 650) and Miscanthus from 6 000 to 22 000 kg/ha (reference yield is 13 590). Figure 4-8 shows that the influence of the yield is very high for both crops. The sensitivity is more marked for the Miscanthus because of the influence of the vegetation carbon stock change from previous land use, which is directly linked to the yield (as modelled). At a lower yield, the un-harvested Miscanthus vegetation is also lower and the carbon credit from vegetation is lower. For instance, at 6 000 kg Miscanthus biomass per ha, the carbon footprint reaches 0.283 kg CO_2eq/kg dry matter and is larger than the Switchgrass footprint at the reference yield of 8 650 kg/ha which scores 0.235 kg CO_2eq/kg dry matter. At about 19 000 kg/ha, the Miscanthus biomass becomes carbon neutral.

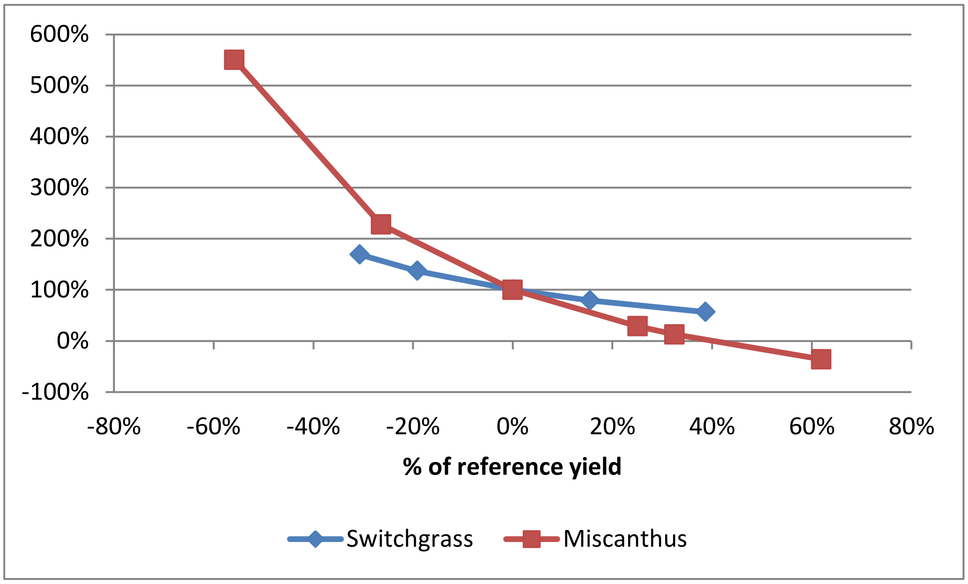

Figure 4-8 : Sensitivity of Switchgrass and Miscanthus carbon footprints to the harvest yield (reference yield is 8 650 and 13 590 kg/ha for SG and MS, respectively, humid basis).

4.3.4 Sensitivity Analysis 4 – Stands' lifetime

The influence of stand lifetime has been assessed throughout the range of 10 to 20 years. The Switchgrass carbon footprint increases by 29% when stand lifetime is reduced from 15 to 10 years, and decreases by 12% when stands are productive during 20 years (Figure 4-9). In fact, the longer the lifetime, the higher the amortization of the burden from land preparation and establishment years. This explains the nonlinear decrease of the carbon footprint.

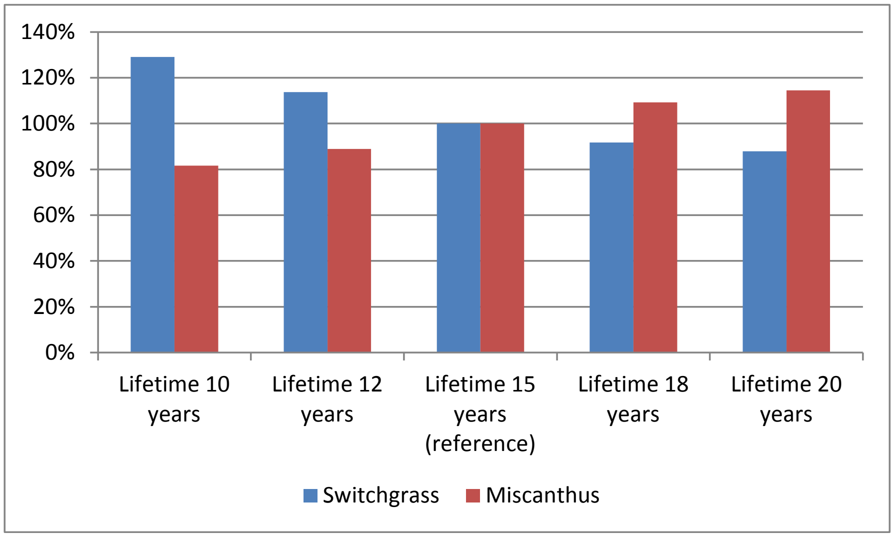

Figure 4-9 : Sensitivity of Switchgrass and Miscanthus carbon footprints to stand lifetime.

Miscanthus displays a reverse trend: its carbon footprint increases with stand lifetime (Figure 4-9). This is a due to the vegetation carbon stock change as a consequence of LUC and to its contribution to the carbon footprint, once reported to the mass of biomass harvested during the lifetime. If LUC carbon was excluded from calculations, the trend would be similar to Switchgrass (results not shown, but available in Appendix E), with a decrease of the carbon footprint when lifetime increases, slightly more marked for Miscanthus than for Switchgrass. In fact, throughout the stands' lifetime, the variation of carbon stock change per kg biomass from LUC (soil and vegetation) demonstrates opposite trends for the two biomass (Figure 4-10).

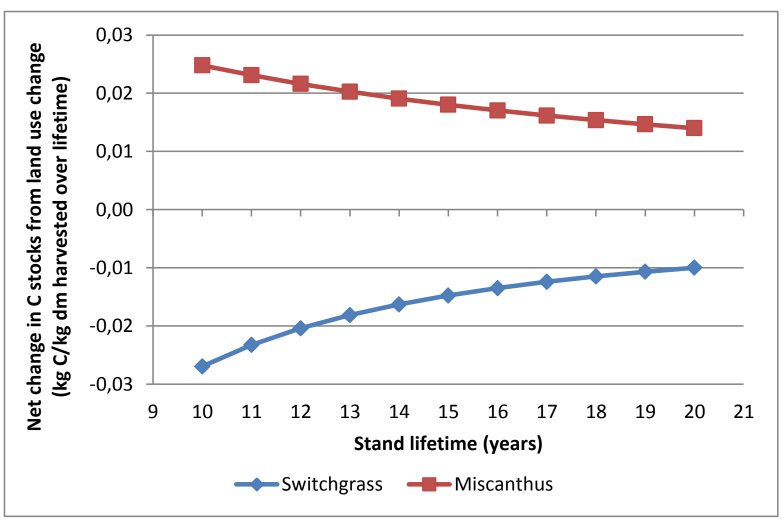

Figure 4-10 : Stand lifetime influence on net change of carbon stock from land use change (soil + vegetation).

4.3.5 Sensitivity Analysis 5 – Soil carbon sequestration rate

Results have shown the significant contribution of LUC carbon to the GHG footprint for both biomass. LUC as a source or sink of C is also largely reported in the literature as a key issue when assessing the GHG life cycle profile of a bioenergy, biofuel, or bioproduct, be it from perennial or annual crops. This is especially of relevance in the case of perennials cropped on cultivated land, because of their reported ability to restore the SOC through an increased sequestration.

So far, the reference scenario has been to consider the default IPCC guidelines and factors to estimate the change in soil C from LUC and to estimate the initial vegetation C stock (of the previous land use), as presented in Figure 3-4. This leads us to consider a soil C change of -0.225 and -0.155 tonne C/ha (C loss) for Switchgrass and Miscanthus, respectively, which finally gives a net loss of 1.6 tonne C/ha for Switchgrass and a sequestration of 2.9 tonne C/ha for Miscanthus, once the C vegetation stock change is added. However, these estimates are debatable, for two reasons. First, as mentioned at the end of section 3.6.1, two different set of factors within the discrete possible values of IPCC factors can lead to very different results for soil C stock change from LUC and subsequent calculations (see simulation in Appendix F). Second, many publications report either no significant SOC change or much higher sequestration rates from perennial cropping. The range of variability from field measurements from the literature is great (for the reasons mentioned in section 3.6.1), and the large uncertainty related to net C sequestration by perennial cropping will certainly remain debatable until more specific (soil, climate, management practices, crop species), comprehensive, and long term data will become available.

The sensitivity analysis consisted in evaluating different net change in soil and vegetation carbon stocks from LUC through changing the soil C sequestration rate within a range of 0 to 2 tonne C/ha.year for both crops. Table 4-1 presents the results on the carbon footprints.

Table 4-1 : Influence of soil carbon sequestration rate on Switchgrass and Miscanthus carbon footprints

Soil C sequestration rate (t C/ha.year)	Switchgrass			Miscanthus		
	Net C stocks change (*) (t C/ha)	Carbon footprint (kg CO2eq/kg dm)	% (reference= 100%)	Net C stocks change (*) (t C/ha)	Carbon footprint (kg CO2eq/kg dm)	% (reference= 100%)
-0.225 (SG reference)	-1.6	0.236	100%			
-0.155 (MS reference)				2.9	0.051	100%
0.0	2.9	0.050	21%	6.0	-0,033	-65%
0.2	6.9	-0,088	-37%	10.0	-0,125	-243%
0.4	10.9	-0,227	-96%	14.0	-0,217	-422%
0.6	14.9	-0,365	-155%	18.0	-0,309	-600%
0.8	18.9	-0,504	-214%	22.0	-0,401	-779%
1.0	22.9	-0,642	-273%	26.0	-0,493	-958%
1.2	26.9	-0,781	-331%	30.0	-0,585	-1136%
1.6	34.9	-1,058	-449%	38.0	-0,768	-1493%
2.0	42.9	-1,335	-566%	46.0	-0,952	-1851%

(*) the vegetation C stock change is kept constant at 2.9 and 6.0 t C/ha for Switchgrass and Miscanthus, resp.

Results confirm that the sensitivity is very high. It is recalled that in the case of an actual sequestration of carbon by the soil (positive rates), no N_2O emission from native soil organic matter mineralization has to be considered (Rochette et al., 2008; implemented in Little et al., 2008, 2013).
Table 4-1 presents a selection of carbon footprint results highlighted for some SOC sequestration rates. This focus is proposed for the following reasons:

- In the light of the sequestration rates reported in the literature and used in LCA studies (see section 3.6.1), it seems reasonable to focus on the lowest sequestration rates;
- According to the conservative approach generally used in LCA studies, in case of doubt and when no rational points can help, it is recommended to discard the option(s) that can lead to an underestimated impact.
- There is also some uncertainty related to the C vegetation stock change, and more specifically to the C vegetation stock value estimated for the previous land use (derived from IPCC guidelines default values) and to our estimate of the C vegetation stock value for the biomass land use because of the large soil depth considered (up to 100 cm). Hence, the C vegetation stock change might have been overestimated. Choosing a lower SOC sequestration rate allows to offset this possible overestimation.

Assuming no soil C loss from LUC and averaging the carbon footprint over the [0 - 0.8 tonne C/ha] range of soil C sequestration rate, the **Switchgrass scores -0.227 kg CO_2eq/kg dry matter biomass**. Similarly, the **Miscanthus average carbon footprint is -0.217 kg CO_2eq/kg dry matter biomass**. Thus, both carbon footprints are roughly the same. Within this range of SOC sequestration rate, the resulting average of the net C stock change annualized over the IPCC 20-year timeframe is 0.55 and 0.7 tonne C/ha.year for Switchgrass and Miscanthus, respectively. These results are in line with the values used for the net C credit from LUC in LCA studies (e.g. Clifton-Brown et al., 2007; Cherubini and Jungmeier, 2010; Follett et al., 2012).

4.4 LCA applications and limits of the study

This study aimed at estimating the life cycle GHG of switchgrass and miscanthus farm production in Ontario according to recommended management practices, as of 2013. All conclusions taken out of the original context of this study must be avoided.
<u>Its results can be used to:</u>

- Characterize the GHG environmental profile of the two biomass studied, identify the "hot spots" and key parameters;
- Identify strengths and weaknesses of each biomass;
- Assess the carbon footprint of product or energy processed from biomass.

<u>The main limitations that could be raised include:</u>

- The uncertainty related to GHG from land use change. With respect to this specific assessment, the study does not allow judging between two approaches that deliver significantly different results. The IPCC approach, whose scope is global, is helpful and convenient owing to its simple parameterization (the three IPCC factors). However, the approach does not provide enough discrimination, it conveys a large uncertainty, and its outcome is very sensitive to the choice of parameters. The second approach, based on estimates from the literature for soil C sequestration, is also uncertain due to the large variability of available data. Even though we are fairly confident with the ability of Switchgrass and Miscanthus to increase soil organic carbon on lands previously used for annual crops, this is to be tempered with possible soil C loss when change occurs on grasslands or abandoned lands.

- The completeness and validity of the inventory data. In particular,
  - Use of secondary data from European LCI databases may affect the validity of results in an Ontario context and more globally, in a North American context;
  - The estimates and assumptions about the life cycle of the products studied (refer to Table 3-2 and Table 3-3).

Finally, LCIA results are relative expressions on global warming potential and do not predict impacts on damage categories like human health or natural ecosystem, or the exceeding of thresholds, safety margins or risks.

4.5 Recommendations

As demonstrated through the contribution and the sensitivity analyses, some production parameters offer the possibility to reduce the carbon footprint. However, an increase of the yield together with an increase of fertilization N input leads to an opposite effect on the footprint. Extending stands' lifetime in case of low LUC contribution (in absolute value), e.g. when it is calculated according to the "IPCC" reference scenario, can lead to a slight change of the carbon footprint. In case of high LUC contribution (in absolute value), e.g. when it is calculated according to the "soil sequestration" scenario, the contribution of other processes is however highly reduced and the benefit from higher yield or lower N input level is weaker.

For future LCA studies on the subject, it is especially recommended to gather comprehensive Ontario specific data for a better modelling that will improve the carbon footprint assessment (see conclusion of the data quality assessment in Appendix D). Such data should address:

- Above- and below-ground mass balance of crop components, and carbon and nitrogen contents;
- Long term soil organic carbon content, at various soil depth, of biomass cropland;
- Soil organic content representative of the various previous land use of relevance (crop land in rotation, grassland, and abandoned land).

Lastly, any carbon credit/emission related to land use change is considered amortized once the soil reaches a new equilibrium. By default, the time period considered for the new equilibrium is the IPCC 20-year horizon. Beyond this timeframe, no credit/emission from LUC should be accounted anymore in any LCA of biomass production (see for instance Cherubini and Jungmeier (2010) who assessed a biorefinery system based on Switchgrass for bioethanol, bioenergy or chemicals).

5 Conclusion

This carbon footprint study strictly follows the framework from ISO14040:44 Standards on LCA. Also, emission calculation and reporting is following guidelines specific to agricultural products and to agricultural products intended for energy use, such as the two GHG Protocol's Agricultural Guidance and Product Standard, and more specifically for GHG from field and from land use change (LUC), the BioGrace guidance and the Roundtable on Sustainable Biofuels methodology which are both in accordance with the European Commission's Renewable Energy Directive requirements. All these methodological guidelines are largely referring to the IPCC's Agriculture methodology whose core principle (the tiered approach) allows the use of country-specific methodology and/or emission factors for more representative assessments than IPCC's defaults could offer.

The carbon footprint is reported to the following functional unit: *"1 kg dry matter of Switchgrass or Miscanthus agricultural biomass, baled, at farm gate, produced in Ontario according to best management practices as of 2013"*. It is calculated over the lifetime of the perennial crops, assumed to be 15 years, including land preparation, planting and establishment years.

Primary data have been collected from several Ontario biomass producers for fieldwork operations, and best management practices are from an Ontario study (Engbers, 2012), while some other data and assumptions have been validated by the OFA and the OSCIA (2013). Direct and indirect N_2O field emissions are comprehensively calculated according to the Tier-2 Canadian-specific IPCC methodology (Rochette et al., 2008) with a focus on the Ontario ecodistricts of relevance for biomass production. All four pools of N inputs are considered for N_2O: mineral N, above- and below-ground residues and native soil organic matter mineralization as a consequence of LUC.

The previous land use combinations considered for Miscanthus and Switchgrass (cropland-grassland-abandoned land) are, nevertheless a corn-wheat-soybean cropland scenario dominates for both biomass crops (75% for Switchgrass and 90% for Miscanthus).

LUC CO_2 is estimated according to two different approaches (or scenarios) for a better evaluation of the sensitivity of the carbon footprint results to the uncertainty related to this source of GHG. Both approaches consider the three C stocks: soil C stock, un-harvested above- and below-ground vegetation C stocks. The IPCC approach is based on the IPCC guidelines and weighing factors for assessing the soil C stock change, while the sequestration approach assumes a positive soil C stock change (i.e. C sequestration) derived from a literature review. Using such data, an average net sequestration from the three stocks totals 0.55 and 0.7 tonne C/ha.year for Switchgrass and Miscanthus, respectively. For both approaches, the vegetation C stock change is estimated from IPCC default data for each previous land use while biomass components for vegetation C stock have been gathered from literature.

Figure 5-1 presents the contributions to the carbon footprint calculated with the two different approaches for GHG from LUC. A major finding of this study is that the LUC contribution can be so significant that it becomes critical to determine how LUC CO_2 is estimated. Consequently, the uncertainty related to the assessment of LUC is carried over to the overall result of the carbon footprint. Uncertainty related to the other data, such as primary data collected for farm operations from biomass producers, and secondary data taken from LCI database (for background processes of the life cycle, e.g. the GHG impact from fertilizer production), becomes less relevant when evaluating the robustness of the results.

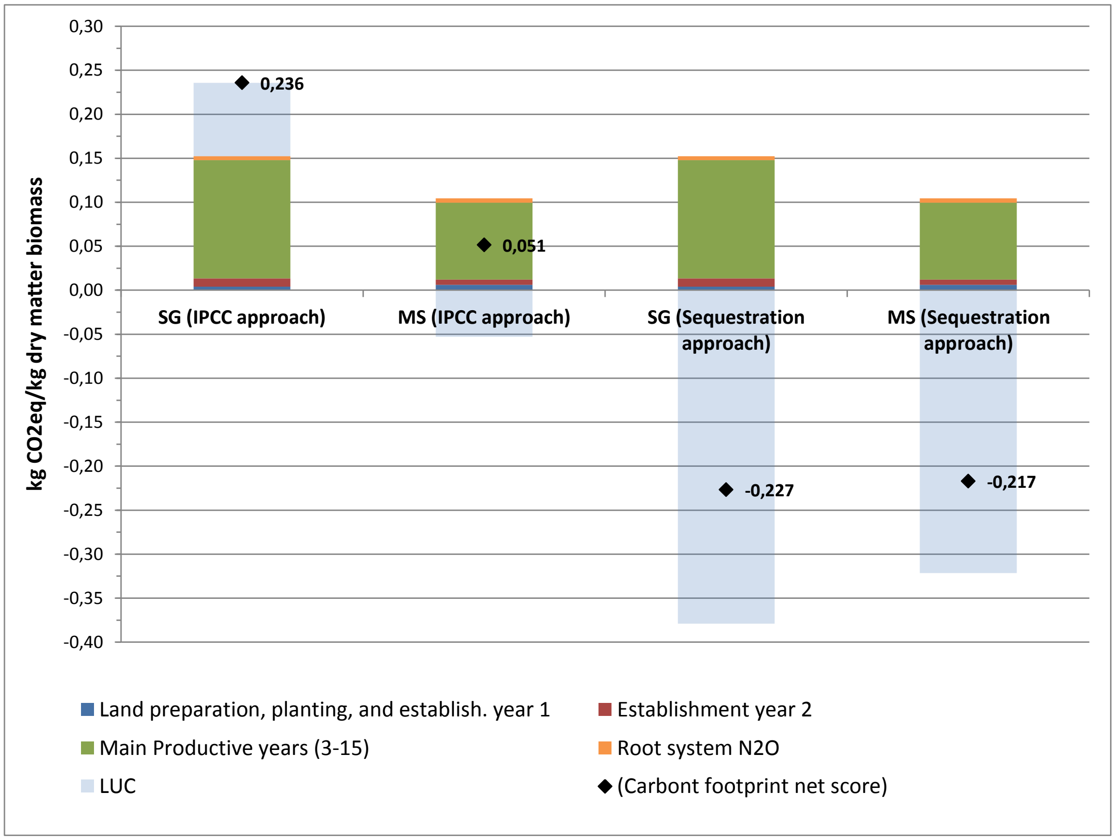

Figure 5-1 : Switchgrass (SG) and Miscanthus (MS) carbon footprint according to two different accounting for LUC: the IPPC approach and the carbon sequestration approach (calculated carbon stock net change of 0.55 and 0.7 tonne C/ha.year for SG and MS, respectively).

In the case of the IPPC approach for Switchgrass, LUC impact is a net emission and contributes for 35% of the footprint, N_2O emission for 35% as well, fertilizer supply for 11%, and the baling and the bale handling operations for 7%. For Miscanthus, LUC offers a net credit corresponding to 51% of GHG emissions, while the other stages contribute for 52%, 17%, and 13% of the emissions, respectively.

In the case of the carbon sequestration approach scenario, LUC offers an important GHG credit and the resulting carbon footprint is negative and similar for both biomass, about -0.22 kg CO_2eq/kg dry matter biomass.

These two scenarios for LUC impact show that the biomass carbon footprint is very sensitive to how LUC impact is assessed. One key recommendation for a more robust assessment of biomass carbon footprint is to gather comprehensive Ontario-specific data for above- and below-ground crop components' mass and carbon and nitrogen contents, long term soil organic carbon content of biomass cropland and of the previous land uses.

Other significant contributors to the carbon footprint are N_2O field emissions from nitrogen inputs and GHG from fertilizer production and supply. It is believed that these impacts have been estimated with confidence throughout this study. A recommendation to producers would be to seek lower fertilizer rates without sacrificing yield, which will also increase profitability. Yearly soil analyses should help determine t an optimal rate. Especially for Miscanthus, a slight decrease of the fertilization rate can lead to a marked reduction of the carbon footprint.

Carbon footprint results have also been found very sensitive to the yield. Producers who obtain higher yields than the average ones considered (8 650 kg biomass/ha at 10% moisture for Switchgrass, 13 590 kg biomass/ha at 13% moisture for Miscanthus) could claim a lower carbon footprint for their own biomass. Conversely, sensitivity of the carbon footprint to stands' lifetime is not very significant. Even more insignificant are stands' establishment failure rate, weed management (chemical vs. mechanical), bales storage (on field vs. on farm). The single fieldwork on which to focus for improvement – although limited – would be the diesel consumption for baling.

Switchgrass and Miscanthus are perennials known as low-input crops (low fieldwork, low N input,). This study demonstrates that GHG impact from producing such a biomass in Ontario is indeed not governed by fieldworks but mostly by soil N_2O emissions concomitant to N inputs and by fertilizer production. Considering LUC can significantly influence the biomass carbon footprint, positively or negatively. There is still too much uncertainty about LUC estimates to conclude with confidence if there is a net impact from cropping Switchgrass and Miscanthus biomass in Ontario, or if the biomass is carbon neutral (no impact) or even if it allows sequestrating carbon. Consequently, a conservative positioning is to consider a carbon footprint about 0.24 kg CO_2eq/kg dry matter biomass for Switchgrass and about 0.05 kg CO_2eq/kg dry matter for Miscanthus.

Lastly, it is worth noting that this study is not a comparative LCA of Switchgrass and Miscanthus biomass. It shall not serve public assertion of superiority of one biomass with respect to the other.

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Appendix A :
Review of carbon footprint methodologies

The content of this Appendix is included in the file
« Appendix_A-Carbon_Footprint_Methodology.xls » provided with this report.

Appendix B : Literature review summary

This Appendix is not applicable.

Appendix C : Data and assumptions

This appendix includes an Excel file with:

- Complete list of the general assumptions
- complete list of intermediate flows (foreground system) and how the inventory has been obtained/modeled
- list of parameters (cut and paste from SimaPro)
- Qualitative description of foreground processes
- Quantitative description of foreground processes (calculations and assumptions)

Appendix D :
Inventory data quality assessment

In addition to the following, the content of this Appendix is included in the file « Appendix_D-Data_Quality.xlsx » provided with this report.

Excel file including :

- The following tables
- Additional comments on the scores attributed
- Recap tables of contribution results (results also available in « Appendix_E-LCA_Results.xlsx »)

D.1 Data quality assessment criteria

Table D-1 shows the criteria that are used for the qualification of inventory data. These criteria concern the reliability and the representativeness of data. It should be noted that this data quality assessment is simplified yet well suited for LCA purposes: it should not complicate the life cycle impact assessment step and it has been designed so as to provide an excellent overview of the type of inventory data collected.

Table D-1: Data quality assessment (quantity and process)

Score	Qualification criteria – Reliability (quantity)
1	Measured or calculated and verified data on site – *This data meets the Reliability/precision criteria required for the study.*
2	Verified data, partly from assumptions OR Measured data but not verified (documents provided by the client or literature) – *This data is considered sufficiently accurate/reliable by the working team for the study.*
3	Non verified data, partly from assumptions OR Estimated data (good estimation performed by an expert) – *This data is considered usable by the working team, but its precision/reliability could be improved.*
4	Data roughly estimated – *This data does not meet the precision/reliability criteria for the study.*
Score	**Qualification criteria – Representativeness (process)**
1	On site data (directly linked to the scope) - *This data meets the Representativeness criteria required for the study.*
2	Good geographical/technological representativeness of the selected process - *This data is considered sufficiently representative by the working team for the study.*
3	Data related to the same process or material but referring to another technology (i.e. process from generic database) - *This data is considered usable by the working team, but its representativeness could be improved*.
4	Data whose geographic and technological representativeness are inadequate. The data is not easily accessible, another process is used to approximate the figures (proxy) - *This data does not meet the Representativeness criteria for the study.*

D.2 Results – data quality assessment

Table D-2 summarizes the data quality assessment results.

The *Reliability* criterion refers to the quantification of the flows (materials and energy, transport distances, waste) while the *Representativeness* criterion refers to the geographic and technological validity and completeness of the selected generic data modules (processes). Finally, the potential contribution to the impacts refers to the effect that the process has on the results. A colour code was added and is presented in Table D-2.

Table D-2: Contribution criteria and data quality

Contribution		Quality	
0-5%	Potentially weak or negligible contribution	1	Meet the criterion
6-10%	Potentially impactful contribution	2	Judged sufficient
11-50%	Potentially high impact contribution	3	Judged usable, but could be improved
51-100%	Potentially very high impact contribution	4	Do not meet the criterion

Generally, a score of 1 is excellent while 4 is reserved for data that should be enhanced to meet the various quality criteria. The processes for which data quality is limited or insufficient are highlighted in red (score of 4) and the processes that could be improved are orange (score of 3).

Table D-3 and Table D-4 present the result of data quality assessment for Switchgrass and Miscanthus, respectively. As for the contribution, the value presents the contribution relative to 100% of the carbon footprint (first section of each table) and relative to 100% of the specific impact of the detailed stage (subsequent sections of each table).

Comments on every quality score given for reliability and representativeness are included in the Appendix file « Appendix_D- Data_Quality.xlsx » provided with this report.

For both biomass, for the stages of establishment year 2, productive years (3-15), and for root system emission, the reliability (quantity) and representativeness (process used for modelling) scores are driven by that of soil direct emissions (N_2O). Onsite measurements of these emissions would be better than modelled emissions (though variability would be inevitable and might not lead to better estimates); Estimates used for N content of crop residues and amount of crop residues are calculated from literature, and would deserve improvement for reliability. On the other hand, the model used for the calculations of N_2O emissions is comprehensive and based on a Canadian-specific methodology (Tier 2 IPCC), mixing Ontario ecodistrict-specific emission factors (for direct N_2O, i.e. most of total N_2O) and default global emission factors (for indirect N_2O, around 15% of total N_2O). Hence, the modelling is judged of good quality. A process-based model would likely be better than a regression model, but it requires a lot more input data (on climate, soil, etc...) and a high expertise.

With respect to LUC, the low quality score of “4” is given due to the issue of C stocks change estimation which has been largely discussed throughout the report. The model used for the calculations of C emissions from LUC is based on a global and simple methodology (Tier 1 IPCC), even though consideration of Canadian and Ontario specificities is introduced to improve the representativeness of estimates. Here again, a process-based model (like CENTURY) would allow balancing C exchanges and likely improve stocks changes estimation.

Table D-3: Process contribution and inventory data quality (Switchgrass)

Life cycle stage / Process	Contribution to impact	Quality	
		Reliabilty (Quantity)	Representativeness (Process)
Switchgrass	**100%**		
Land preparation, planting, and establishment year 1	2%	2	2
Establishment year 2	4%	3	2
Main Productive years (3-15)	57%	3	2
Root system N2O	2%	3	2
LUC	35%	4	3
Land preparation, planting, and establish. year 1	**100%**		
Soil direct emissions	4%	3	2
Inputs (pesticides, seeds) and Transport of inputs	14%	2	3
Tillage	40%	2	2
Pesticides application	6%	2	2
Sowing	5%	2	2
Mowing	6%	2	2
Swathing and Raking	11%	2	2
Baling and Bales handling	3%	3	2
Transport of people	10%	3	2
Establishment year 2	**100%**		
Soil direct emissions	62%	3	2
Fertilizer	20%	2	3
Other inputs (pesticides) and Transport of inputs	2%	2	2
Weed management	4%	2	2
Swathing and Raking	5%	2	2
Baling and Bales handling	6%	3	2
Fertilising	1%	2	2
Transport of people	0%	3	2
Main Productive years (3-15)	**100%**		
Soil direct emissions	63%	3	2
Fertilizer	18%	2	3
Transport of inputs	1%	2	2
Swathing and Raking	5%	2	2
Baling and Bales handling	12%	3	2
Fertilising	1%	2	2
Transport of people	0%	3	2

Table D-4: Process contribution and inventory data quality (Miscanthus)

Life cycle stage / Process	Contribution to impact	Quality	
		Reliabilty (Quantity)	Representativeness (Process)
Miscanthus	**100%**		
Land preparation, planting, and establishement year 1	4%	2	3
Establishment year 2	4%	3	2
Main Productive years (3-15)	55%	3	2
Root system N2O	3%	3	2
LUC	34%	4	3
Land preparation, planting, and establish. year 1	**100%**		
Inputs (pesticides, rhizomes) and Transport of inputs	63%	2	3
Tillage	19%	2	2
Pesticides application	3%	2	2
Planting	8%	3	3
Mowing	3%	2	2
Transport of people	4%	3	2
Establishment year 2	**100%**		
Soil direct emissions	61%	3	2
Fertilizer	20%	2	3
Other inputs (pesticides) and Transport of inputs	2%	2	2
Weed management	4%	2	2
Harvesting	3%	2	2
Baling and Bales handling	8%	3	2
Fertilising	1%	2	2
Transport of people	0%	3	2
Main Productive years (3-15)	**100%**		
Soil direct emissions	62%	3	2
Fertilizer	18%	2	3
Transport of inputs	1%	2	2
Harvesting	3%	2	2
Baling and Bales handling	15%	3	2
Fertilising	1%	2	2
Transport of people	0%	3	2

Appendix E : Results

The content of this Appendix is included in the file
« Appendix_E-LCA_Results.xlsx » provided with this report.

Excel file including :

- Results and contributions
- Inventory of elementary flows from SimaPro
- Characterized results
- Sensitivity analyses
- Non characterized flows

Appendix F : Influence of the choice of IPPC's management and input factors on soil C and vegetation C stocks change due to land use change

The table below presents simulated results of net carbon change for Switchgrass and Miscanthus when both the IPCC *management practices* factor and *input level* factor used for estimating the previous land use C stock are varied along the possible range. The intent is to demonstrate the extent of variability related to the choice for these factors. Results of this simulation are not used elsewhere.

- The simulation has been performed only for the case of cropland as previous land use, meaning that factors for the two other previous land uses of our study - grassland and abandoned land - are the same as the ones presented in Figure 3-4 (section 1.1 of the figure). The reason is for the sake of simplicity, given that results of this simulation are not used elsewhere. Furthermore, this previous land use is the driver of the averaged previous land use (90% for Miscanthus, 75% for Switchgrass).
- Throughout the simulation, the *land use* factor Flu (the first of the three IPCC factors) is kept constant, at the value corresponding to *Long term cultivated*, i.e. 0.71, because we are confident with this choice (in fact, other choices are not relevant).
- Also, the vegetation C stocks are not modified (same as presented in Figure 3-4, section 1.2 of the figure). There is certainly some uncertainty with the assessment of vegetation carbon stocks, and consequently with the vegetation carbon stock change derived, but it is out of scope of this simulation.
- Biomass land use factors for *land use*, *management practices* and *input level* are also kept constant (0.71; 1.13 and 0,91 respectively, as presented in Figure 3-4, section 1.1 of the figure).

A negative value means a net C loss; a positive value means a C sequestration
Bold values are the reference scenario of the study, which gives 1.6 tonne C/ha lost for Switchgrass and 2.9 tonne C/ha sequestered for Miscanthus.

The table on the next page details the different management and input categories (European Commission, 2010)

Input Factor (Fi)		Management Factor (Fmg)		Net change in C stocks from land use change (t C/ha)	
				Switchgrass	Miscanthus
Low	0,91	Full tillage	1.00	3.9	9.4
		44% Full-till, 25% Reduced, 31% No-till	1.072	1.7	6.8
		Reduced tillage	1.09	1.1	6.1
		No tillage	1.16	-1.0	3.6
Medium	**1,00**	Full tillage	1.00	0.9	5.8
		44% Full-till, 25% Reduced, 31% No-till	**1.072**	**-1.6**	**2.9**
		Reduced tillage	1.09	-2.2	2.2
		No tillage	1.16	-4.5	-0.6
High without manure	1,11	Full tillage	1.00	-2.8	1.4
		44% Full-till, 25% Reduced, 31% No-till	1.072	-5.5	-1.9
		Reduced tillage	1.09	-6.2	-2.7
		No tillage	1.16	-8.8	-5.8
High with manure	1,38	Full tillage	1.00	-11.9	-9.5
		44% Full-till, 25% Reduced, 31% No-till	1.072	-15.2	-13.5
		Reduced tillage	1.09	-16.1	-14.5
		No tillage	1.16	-19.3	-18.4

Table 3

Guidance on management and input for cropland and perennial crops

Management/ Input	Guidance
Full-tillage	Substantial soil disturbance with full inversion and/or frequent (within year) tillage operations. At planting time, little (e.g. < 30 %) of the surface is covered by residues.
Reduced tillage	Primary and/or secondary tillage but with reduced soil disturbance (usually shallow and without full soil inversion) and normally leaves surface with > 30 % coverage by residues at planting.
No till	Direct seeding without primary tillage, with only minimal soil disturbance in the seeding zone. Herbicides are typically used for weed control.
Low	Low residue return occurs when there is due to removal of residues (via collection or burning), frequent bare-fallowing, production of crops yielding low residues (e.g. vegetables, tobacco, cotton), no mineral fertilisation or nitrogen-fixing crops.
Medium	Representative for annual cropping with cereals where all crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g. manure) is added. Also requires mineral fertilisation or nitrogen-fixing crop in rotation.
High with manure	Represents significantly higher carbon input over medium carbon input cropping systems due to an additional practice of regular addition of animal manure.
High without manure	Represents significantly greater crop residue inputs over medium carbon input cropping systems due to additional practices, such as production of high residue yielding crops, use of green manures, cover crops, improved vegetated fallows, irrigation, frequent use of perennial grasses in annual crop rotations, but without manure applied (see row above).