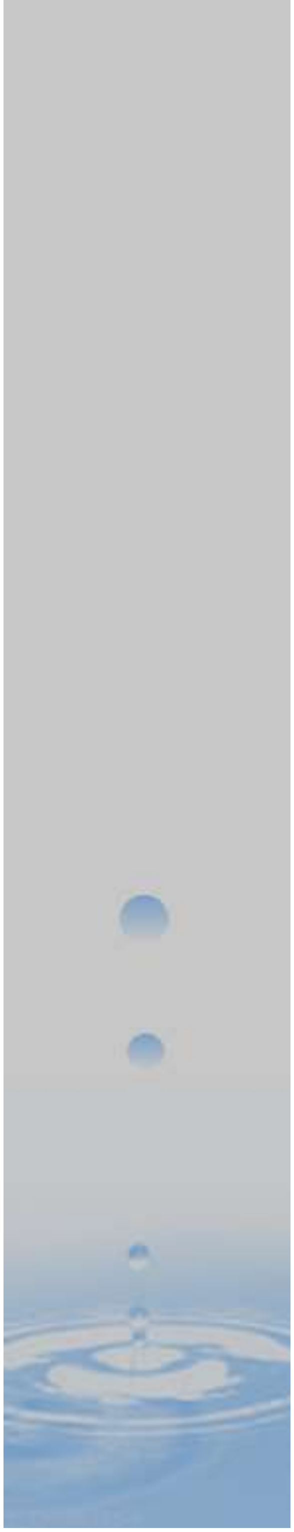
IEA Bioenergy
Task 39
Commercializing 1st- and 2nd- Generation Liquid Biofuels from Biomass

Report T39-T1a   24 January 2011



BIODIESEL GHG EMISSIONS, PAST, PRESENT, AND FUTURE

A REPORT TO IEA BIOENEGY TASK 39

AUTHOR:

Don O'Connor

(S&T)^2 Consultants Inc.

11657 Summit Crescent
Delta, BC
Canada, V4E 2Z2

Report T39-T1a. 24 January 2011

Executive Summary

IEA Bioenergy is an international collaborative agreement set up in 1978 by the International Energy Agency (IEA) to improve international co-operation and information exchange between national bioenergy RD&D programmes. The IEA Bioenergy Vision is “To realise the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, to provide a substantial contribution to meeting future energy demands.”

The IEA Bioenergy aim is “To facilitate, co-ordinate and maintain bioenergy research, development and demonstration through international co-operation and information exchange, leading to the deployment and commercialization of environmentally sound, sustainable, efficient and cost-competitive bioenergy technologies.”

As part of IEA Bioenergy Task 39’s ongoing program of promoting the commercialization of biofuels, the Task commissions reports that help to address specific areas of interest to the members. Task 39 is an ideal mechanism for bridging the Atlantic and transferring knowledge between member countries.

The energy balance and greenhouse gas emissions of biofuels remain a controversial topic in the popular press, with government policy makers, and within the academic community. Most of the discussion is based on the existing (or past) performance of biofuel technologies and therefore may not be representative of future developments in the industry.

This project addresses three specific issues with respect to the GHG emissions from the production and use of biodiesel.

1. The GHG emissions for biodiesel are estimated for the years 1995, 2005, and 2015. The GHGenius model is used for these calculations, as it is well set up to model biodiesel production with multiple feedstocks over different time periods.
2. Investigating the production parameters for specific aspects of similar feedstock in different countries may allow for the identification of any differences in GHG emissions for the same process in different countries.
3. The third part of the work is to analyze some of the estimates of GHG emissions that have been made for biodiesel production. The intent is not to determine which one is correct or best, but to understand why there are differences.

Life cycle assessment is a "cradle-to-grave" (or “well to wheels”) approach for assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product selection.

The available data on the supply chain for rapeseed and soybean biodiesel would indicate that the GHG emissions for these vegetable oil biodiesel fuels have decreased from 1995 to 2005, and if the present trends continue there should be further reductions in the emissions in the future and these are projected for the year 2015. The emissions for rapeseed biodiesel have been declining at 1.9% per year and for soybean biodiesel at 0.6% per year. These rates may be conservative because the quality of the data for some parts of the supply chain has been poor. The results for rapeseed biodiesel are summarized below.

Table ES- 1 Rapeseed Biodiesel GHG Emissions vs. Time

	Diesel Fuel	Rapeseed Biodiesel		
	1995	1995	2005	2015
	g CO_2eq/GJ (HHV)			
Fuel dispensing	131	150	157	122
Fuel distribution and storage	465	1,311	1,219	1,150
Fuel production	5,589	7,634	7,535	7,162
Feedstock transmission	1,015	949	956	980
Feedstock recovery	7,746	5,290	4,540	2,851
Land-use changes, cultivation	130	25,802	21,074	15,785
Fertilizer manufacture	0	11,743	9,743	7,981
Gas leaks and flares	3,221	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-126	-19,032	-20,784	-23,172
Sub-Total	18,170	33,846	24,441	12,860
Combustion Emissions	69,956	1,690	1,740	1,735
Grand Total	88,126	35,536	26,181	14,595
% Reduction		59.6	70.3	83.4

While the methodology used for these calculations is different than that used by the European Union for the GHG emission reductions required under the Renewable Energy Directive, the fact that there are reductions in GHG emissions over time should also become apparent once operators start to use actual data in the calculation of GHG emissions rather than using the default values in the RED. The reduction of more than 20 percentage points found in this work from 1995 to 2015 bodes well that the existing rapeseed biodiesel with a default GHG reduction of 38% will easily be able to meet the 50% reduction required in 2017 under the RED.

As a check on the continuation of the trends in GHGenius a number of areas for improvement in the GHG emissions have been identified and the emissions impact of each has been estimated. These include no till management practices that reduce fuel use, increase soil carbon, the use of controlled release nitrogen fertilizer to reduce N_2O emissions, increased oil content of the seeds and lower energy consumption in the oilseed crushers and biodiesel processors. All of the improvements identified are currently being practiced in some parts of the world but not by all participants in the supply chain. The greatest area for improvement is in the feedstock production. The potential GHG improvements in oilseed crushing and biodiesel production are relatively small.

The cumulative impact of all of the changes identified is shown in the following table. It can be seen that the impact of these changes is similar to the results from the continuation of the existing trends through to the year 2015.

Table ES- 2 Rapeseed Biodiesel GHG Emissions vs. Time

	Diesel Fuel	Rapeseed Biodiesel		
	1995	1995	2005	Impact of all potential improvements
	g CO_2eq/GJ (HHV)			
Fuel dispensing	131	150	157	157
Fuel distribution and storage	465	1,311	1,219	1,219
Fuel production	5,589	7,634	7,535	6,967
Feedstock transmission	1,015	949	956	881
Feedstock recovery	7,746	5,290	4,540	2,577
Land-use changes, cultivation	130	25,802	21,074	12,136
Fertilizer manufacture	0	11,743	9,743	8,814
Gas leaks and flares	3,221	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-126	-19,032	-20,784	-16,732
Sub-Total	18,170	33,846	24,441	16,019
Combustion Emissions	69,956	1,690	1,740	1,740
Grand Total	88,126	35,536	26,181	17,759
% Reduction		59.6	70.3	79.8

The agricultural practices and GHG emission results for essentially the same crop are somewhat different in Canada, the UK and Germany. Germany benefits from high yield and good nitrogen fertilizer utilization and as a result the biodiesel produced there has the lowest GHG emissions when all other factors are held constant.

Much larger differences in GHG emissions have been identified from regional factors that are generally beyond the control of the feedstock producer. The production of nitrogen fertilizer is quite different from region to region, with different products being produced and different technologies being employed. European regions appear to use more nitrate-based fertilizers (ammonium nitrate, calcium nitrate, etc.) whereas in North America the ammonium-based fertilizers are more prevalent (ammonia and urea). There are large differences in the GHG emissions associated with the different types of fertilizers and this has a significant impact on the biodiesel lifecycle emissions.

Some of the largest differences in GHG emissions result from the application of the fertilizer and are mostly dependent on the natural environment. Individual producers can impact the quantity of N_2O generated by varying the timing of fertilizer application and by the use of slow release products, but natural conditions will dominate these emissions and the differences from region to region.

There is still much to be learned about the N_2O production from fertilizer application and of the three regions investigated only Canada uses IPCC Tier 2 emission factors in its National GHG Inventory. The emission factors used here for the UK and Germany may be different than the actual factors in the field but, given the different moisture scenarios, it is highly likely that the N_2O emissions in the UK and Germany are in fact significantly higher than they are in Canada. These results are summarized in the following table.

Table ES- 3 Biodiesel GHG Emission Comparison with Regional Factors

	Canada	UK	Germany
	g CO_2eq/GJ (HHV)		
Fuel dispensing	157	157	157
Fuel distribution and storage	1,219	1,219	1,219
Fuel production	7,535	7,535	7,535
Feedstock transmission	956	956	956
Feedstock recovery	7,609	5,326	4,312
Land-use changes, cultivation	13,985	42,334	24,770
Fertilizer manufacture	12,909	24,468	18,539
Gas leaks and flares	0	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-25,002	-9,425	-19,216
Total	19,369	72,571	38,273

There are some significant differences in the projected GHG emissions for the same biofuel from using different models and calculators. Some of these differences are caused by input differences that are only partially accounted for by regional differences in practices.

The methodology employed in all of the European models results in high emissions in the biodiesel production stage. This is caused by the assumption that all of the methanol is oxidized in the process. In actuality some of the fossil carbon replaces some of the biogenic carbon in the feedstock but the biogenic carbon is present in the glycerine. The energy allocation approach used in these models does not consider the use of the glycerine nor the potential for the biogenic carbon in the glycerine to replace fossil carbon in the applications.

In the examination of the various models it was apparent that most models rely on a narrow set of reference material for choosing the input parameters. Not only are most of the sources 15 to 20 years old, but also it is not apparent how many of the parameters were arrived at. As economic operators begin to comply with the various sustainability criteria being put into regulation it is likely that regulators will find that the emissions for many stages of the lifecycles are significantly below the default values in the various tools and calculators that are available. While this is not expected to surprise the regulators that understand how the tools were developed, it may surprise many interested observers that the actual performance is so much better the models project. Careful communications will be required to educate the observers about how this situation arose.

Most of the models contain data and emission factors for major inputs into the biodiesel lifecycle stages that are beyond the direct control of the economic operators and will not be updated as operators move to comply with the new regulations. Emission factors for fertilizers, pesticides, and chemicals such as methanol need to be reviewed in many of the tools, as the current data is very old and poorly documented. Some calculators do not provide sufficient flexibility to account for the variation in producer inputs. One emission factor for nitrogen fertilizer is clearly inadequate to account for the various products and different production processes that are available.

There are also significant regional variations in emission factors caused by local environmental conditions and soil types that can impact the GHG emissions of biofuel feedstocks. The models and calculators need to have the flexibility to model these specific conditions accurately.

In 2009, a similar study was undertaken for Task 39 ((S&T)^2 Consultants inc, 2009) looking at the expected change in GHG emissions for ethanol produced from corn. The GHG emissions for gasoline and ethanol from that study are shown in the following table.

Table ES- 4 Comparison of GHG Emissions - Gasoline and Ethanol

Fuel	Gasoline		Ethanol		
Feedstock	Crude Oil		Corn		
Year	1995	2015	1995	2005	2015
	g CO_2 eq/GJ (HHV)				
Fuel dispensing	118	90	185	181	142
Fuel distribution and storage	656	507	1,107	1,109	1,124
Fuel production	11,181	12,162	35,012	28,294	19,085
Feedstock transmission	1,084	903	1,004	1,009	1,031
Feedstock recovery	7,257	8,724	12,012	10,550	7,348
Land-use changes, cultivation	8	15	21,827	20,987	20,369
Fertilizer manufacture	0	0	8,261	7,033	6,215
Gas leaks and flares	3,486	1,688	0	0	0
CO_2, H_2S removed from NG	0	0	0	0	0
Emissions displaced	-65	-137	-18,490	-17,934	-17,219
Sub-Total	23,725	23,951	60,919	51,229	38,095
Combustion emissions	62,917	64,813	3,058	2,237	1,973
Grand Total	86,642	88,764	63,977	53,466	40,068
% Reduction			26.2	39.0	54.9

Between 1995 and 2015 it is expected that the GHG emissions for corn ethanol will be reduced by 28.7 percentage points. For the same period this work found a similar trend but a slightly lower magnitude of change with rapeseed biodiesel GHG emissions being reduced by 23.8 percentage points.

There are significant differences in the two lifecycles and one shouldn't expect the reductions to be identical. One of the differences in the two systems is the amount of energy (and thus the GHG emissions created) used in the fuel production process. Much more energy is used to manufacture ethanol than biodiesel and the ethanol industry has a well demonstrated history of reducing the emissions, whereas there is little evidence of similar reductions in the biodiesel production process.

Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

IEA Bioenergy is an international collaborative agreement set up in 1978 by the International Energy Agency (IEA) to improve international co-operation and information exchange between national bioenergy RD&D programmes. The IEA Bioenergy Vision is “To realise the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, to provide a substantial contribution to meeting future energy demands.”

The IEA Bioenergy aim is “To facilitate, co-ordinate and maintain bioenergy research, development and demonstration through international co-operation and information exchange, leading to the deployment and commercialization of environmentally sound, sustainable, efficient and cost-competitive bioenergy technologies.”

Twenty-three countries plus the European Commission, take part in IEA Bioenergy: Australia, Austria, Belgium, Brazil, Canada, Croatia, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Korea, The Netherlands, New Zealand, Norway, South Africa, Sweden, Switzerland, Turkey, the United Kingdom, the USA and the European Commission. Work in IEA Bioenergy is carried out through a series of Tasks, each having a defined work programme. Each participating country pays a modest financial contribution towards administrative requirements, shares the costs of managing the Tasks and provides in-kind contributions to fund participation of national personnel in the Tasks.

1.1 TASK 39 LIQUID BIOFUELS

One of the Tasks is Task 39, Commercialising Liquid Biofuels from Biomass. The Task is currently composed of 15 countries and a regional association, including Australia, Austria, Brazil, Canada, Denmark, the European Union, Finland, Germany, Japan, the Netherlands, Norway, South Africa, South Korea, Sweden, the United States and the United Kingdom. The Task brings together leading researchers, government officials, and industry pioneers in a bid to successfully introduce biofuels for transportation into the commercial marketplace. The objectives of this Task are to:

- Provide information and analyses on policy, markets and implementation issues (including regulatory and infrastructure development) that will help participants encourage commercialization of 'first-generation' and 'second-generation' liquid biofuels as a replacement for fossil-based fuels, by continuing the deployment of 'first-generation' fuels and supporting development of 'second-generation' biofuels.
- Catalyze cooperative research and development projects that will help participants develop improved, cost-effective processes for the production of 'second-generation' liquid biofuels.
- Provide information dissemination, outreach to stakeholders, and coordination with other related groups.

As part of Task 39’s ongoing program of promoting the commercialization of biofuels, the Task commissions reports that help to address specific areas of interest to the members. Task 39 is an ideal mechanism for bridging the Atlantic and transferring knowledge between member countries.

Previous work for IEA Bioenergy Task 39 considered the GHG emissions of corn ethanol ((S&T)^2, 2009) and how the emissions have changed over time. A number of organizations have inquired about doing the same type of analysis for biodiesel. This work is designed to address this need.

1.2 SCOPE OF WORK

This project addresses three specific issues with respect to the GHG emissions from the production and use of biodiesel.

1.2.1 Biodiesel GHG Emissions over Time

Lifecycle Assessment work on biodiesel production pathways has shown that the biodiesel production process itself has a relatively small impact on the total lifecycle emissions. The emissions associated with feedstock production and oilseed crushing has a larger impact on the overall results. Good quality, long term data on crop production is available for some parameters, such as yield (FAO and national agriculture agencies), some information on issues such as fertilizer application rates is available for some crops in some countries but it is generally not as good a quality as yield data (USDA, DEFRA and others), and finally good data on direct energy use for specific crops is difficult to obtain for most crops in most regions.

With the data that is available, it is possible to establish data trends for some of the major inputs for biodiesel feedstocks and determine the impact they have on the lifecycle GHG emissions of biodiesel production. Even if other input parameters are held constant, it will be possible to conservatively evaluate how the lifecycle emissions for biodiesel are changing over time and make some projections into the future based on historical trends. The feedstocks considered would be rapeseed/canola, soybeans, and palm oil.

Time series data sources that are available include US data for soybeans, some Canadian data for Canola (rapeseed). In Europe, there is some information available on rapeseed production. Other data sources will be investigated as part of this project. The emphasis will be on production in the UK and in Germany due to their membership in Task 39 and on the size of the agricultural sectors.

The GHG emissions for biodiesel are estimated for the years 1995, 2005, and 2015. The GHGenius model is used for these calculations, as it is well set up to model biodiesel production with multiple feedstocks over different time periods.

1.2.2 Regional Differences in GHG Emissions

Investigating the production parameters for specific aspects of similar feedstock in different countries may allow for the identification of any differences in GHG emissions for the same process in different countries. This may also allow for the identification of best practices that will allow other countries to improve their production processes.

1.2.3 Comparison of Biodiesel GHG Emissions using Different Methodologies

There is a wide range of estimates available on the lifecycle GHG emissions for biodiesel production. Some of the differences are understandable as different feedstocks are used but, even when the same feedstock is used, there can be significant differences between studies. It is possible that using data from different periods causes some of the differences, different production practices employed in different regions, and different climatic conditions. Another factor that could influence the results is different allocation methods for co-products employed by different studies. The wide range of results is causing uncertainty for some policy makers and a greater understanding of what drives these results is required. The third objective of the work, therefore, is to try to identify the drivers that cause the results to be different and, where possible, explain why the differences exist.

The third part of the work is to analyze some of the estimates of GHG emissions that have been made for biodiesel production. The estimates that are analyzed include the latest BioGrace model (Version 2) estimates for the EU Renewable Energy Directive, the US EPA RFS2 analysis, the UK RFTO Calculator (Version 1.0 Build 48), the Dutch calculator developed by ECOFYS for SenterNovem (Version 2.1), GREET (Version 1.8d and California versions), and GHGenius. The biodiesel systems considered for this part of the project would use the following feedstocks: rapeseed/canola, soybeans, used cooking oil, and palm oil. Not all of the feedstocks can be analyzed in all of the tools but all that can be analyzed will be included. These are summarized below.

Table 1-1 Feedstock and GHG Tool matrix

	Rapeseed	Soy	Palm	Used Cooking Oil
GHGenius	X	X	X	X
US EPA RFS2		X		X
CARB LCFS		X		
GREET		X		
UK RFTO	X	X	X	X
SenterNovem	X	X	X	X
BioGrace	X	X	X	X

The intent is not to determine which one is correct or best, but to understand why there are differences. We know that there are different assumptions that go into each one about the data that is used. Some use deliberately conservative default values and others use industry average values, but a comparison of the actual values used will be informative to help explain the different model results. In other cases, there are fundamental differences in agricultural practices. For example, about 80% of the nitrogen fertilizer used in Europe is a form of ammonium nitrate whereas in North America, ammonium nitrate accounts for less than 20% of the nitrogen fertilizer used. The GHG emissions from ammonia nitrate are much higher than they are for urea or ammonia solutions and the degree to which this drives different results will be investigated for the various crops. For crops like soybeans, the impact of fertilizer types is expected to be minimal but for crops like rape/canola, the impact is likely very significant.

The impact of different co-product allocation approaches will also be investigated as this can have a large impact on the calculated results. Co-product allocation is a major issue in most LCA work and different approaches may explain some of the variation in the results.

2. LIFE CYCLE ASSESSMENT

As environmental awareness increases, governments, industries and businesses have started to assess how their activities affect the environment. Society has become concerned about the issues of natural resource depletion and environmental degradation. The environmental performance of products and processes has become a key operational issue, which is why many organizations are investigating ways to minimize their effects on the environment. Many have found it advantageous to explore ways to improve their environmental performance, while improving their efficiency, reducing costs and developing a “green marketing” advantage. One useful tool is called life cycle assessment (LCA). This concept considers the entire life cycle of a product.

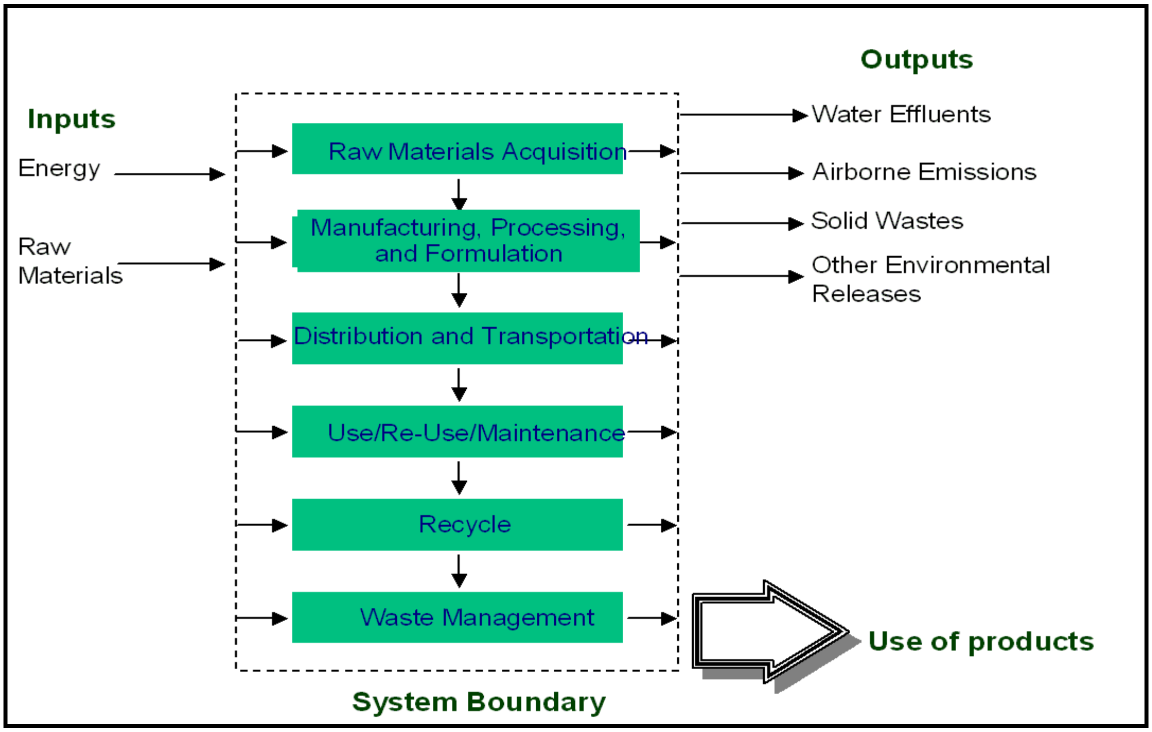
Life cycle assessment is a "cradle-to-grave" (or “well to wheels”) approach for assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product selection.

Specifically, LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:

- **Compiling** an inventory of relevant energy and material inputs and environmental releases;
- **Evaluating** the potential environmental impacts associated with identified inputs and releases;
- **Interpreting** the results to help make more informed decisions.

The term "life cycle" refers to the major activities in the course of the product's life span from its manufacture, use, maintenance, and final disposal; including the raw material acquisition required to manufacture the product. The following figure illustrates the typical life cycle stages that can be considered in an LCA and the quantified inputs and outputs.

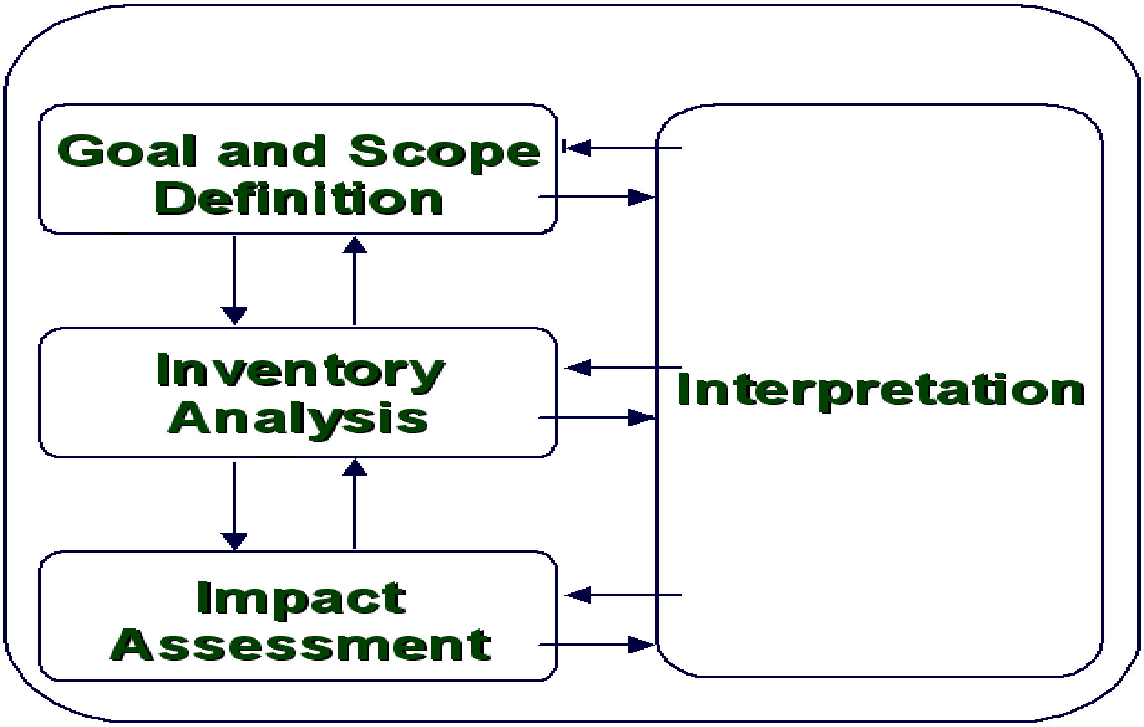
Figure 2-1 Life Cycle Stages



The LCA process is a systematic, iterative, phased approach and consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation as illustrated in the following figure:

1. *Goal Definition and Scoping* - Define and describe the product, process or activity. Establish the context in which the assessment is to be made, and identify the boundaries and environmental effects to be reviewed for the assessment.
2. *Inventory Analysis* - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, wastewater discharge).
3. *Impact Assessment* - Assess the human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.
4. *Interpretation* - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

Figure 2-2 Phases of a LCA



2.1 ISO LIFE-CYCLE ASSESSMENT STANDARDS

The concept of life-cycle assessment emerged in the late 1980’s from competition among manufacturers attempting to persuade users about the superiority of one product choice over another. As more comparative studies were released with conflicting claims, it became evident that different approaches were being taken related to the key elements in the LCA analysis:

- Boundary conditions (the “reach” or “extent” of the product system);
- Data sources (actual vs. modeled); and
- Definition of the functional unit.

In order to address these issues and to standardize LCA methodologies and streamline the international marketplace, the International Standards Organization (ISO) has developed a series of international LCA standards and technical reports under its ISO 14000 Environmental Management series. In 1997-2000, ISO developed a set of four standards that established the principles and framework for LCA (ISO 14040:1997) and the requirements for the different phases of LCA (ISO 14041-14043). The main contribution of these ISO standards was the establishment of the LCA framework that involves the four phases in an iterative process:

- Phase 1 - Goal and Scope Definition;
- Phase 2 - Inventory Analysis;

- Phase 3 - Impact Assessment; and
- Phase 4 - Interpretation

By 2006, these LCA standards were consolidated and replaced by two current standards: one for LCA principles (ISO 14040:2006); and one for LCA requirements and guidelines (ISO 14044:2006). Additionally, ISO has published guidance documents and technical reports (ISO 14047-14049) to help illustrate good practice in applying LCA concepts. The following table summarizes the ISO standards and technical reports for Life-Cycle Assessment.

The ISO 14040:2006 standard describes the principles and framework for life cycle assessment, including definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. ISO 14040:2006 covers life cycle assessment (LCA) studies and life cycle inventory (LCI) studies. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA. The intended application of LCA or LCI results is considered during definition of the goal and scope, but the application itself is outside the scope of this International Standard.

2.2 OVERVIEW OF CURRENT USES OF LIFE CYCLE ASSESSMENT

To date LCA has been applied in evaluating the relative environmental performance of alternative biofuel options with the primary aim of informing industry, government, Environmental Non-governmental Organization (ENGO) and consumer decision-making. Studies have been completed by LCA practitioners in consulting firms, academia, ENGOs, industry, and government. The quality of the studies has varied but over the last decade, on average, study quality has improved due to method development, data availability and higher client expectations.

A few examples of uses of biofuels' LCAs by various decision makers include the following.

- Industry: Through an examination of the results of a LCA of their biofuel production process, a producer may determine where in the process or supply chain an improvement could be made to lower their resource use or environmental discharges. The saying, "what is measured can be managed" is key. Quantifying the resource use/environmental discharges associated with the full life cycle of a biofuel allows industry to move forward toward managing these impacts.
- Government: As will be discussed in more detail below, LCAs of biofuels have been utilized for determining preferred biofuel pathways (feedstock/fuel production) for receiving government funding under biofuels' expansion programs.
- ENGOs: These organizations have utilized LCAs of biofuels to support their positions in calling for increased attention to broad sustainability issues in expansion of biofuel production.
- Consumers: Results of biofuels' LCAs have been presented by various organizations and utilized indirectly in advertising campaigns with the hope of influencing consumer choice with respect to fuel and vehicle options (e.g., purchase of a flexible fuel vehicle so as to have the potential to utilize a high level ethanol/gasoline (E85) blend).

2.2.1 Role of LCA in Public Policies/Regulations

Life cycle assessment’s role in public policy development to date has been focused on informing public policy positions of industry (e.g., General Motors’ decision to support ethanol) and government. In a limited set of cases, LCA has had a more direct role. For example, under the US Renewable Fuel Standard resulting from the Energy Policy Act of 2005, some renewable fuels (e.g., those from selected lignocellulosic feedstocks) that were expected to have lower life cycle environmental impacts through a weighting system that “rewarded” such pathways. This and other similar programs, however, have not required detailed LCA. Generally, although LCA has informed public policy positions it has not been the **basis** of public policies; in particular, those that have binding targets directly related to the application of the LCA method.

This appears to be changing. Over the past few years there have been several announcements related to incorporating life cycle-based standards directly into climate change regulations for transportation fuels. These regulatory initiatives include those covering all transportation fuels in a particular jurisdiction, as well as the more numerous initiatives, which are focused on biofuels. One of the most prominent initiatives is California’s Low Carbon Fuel Standard (LCFS), which will consider all light-duty transportation fuels sold into State (State of CA 2007). The United Kingdom’s Renewable Transportation Fuel Obligation Programme (RTFO), the German Biofuels Ordinance, the European Union’s Renewable Energy Directive (RED) and the Fuels Directive, and the U.S. Energy Independence and Security Act of 2007 all focus on biofuels. In Canada and the U.S., other federal, state, and provincial governments have declared interest in adopting similar low carbon fuel standards (e.g., British Columbia, Ontario, Minnesota, Massachusetts). The programs are currently under development but they will require that the life cycle GHG emissions associated with the production of relevant biofuels (and in some cases, other fuels) be quantified. They will be the first regulations that will be based on systematic LCA.

Two types of programs are appearing, in one type an emissions threshold is established and then an LCA is undertaken to establish whether or not a particular fuel pathway meets or exceeds that threshold. This is a go no go type of regulation, the EU RED and the US RFS2 programs are this type of regulation. The other type of regulation attaches a particular value (such as carbon intensity) to each fuel or fuel component and a target is established that requires obligated parties to meet the target through some combination of using components with the lowest CI achievable and the mix of fuels or components employed. The EU Fuels Directive and the California LCFS fall into this second category. Both programs require the use of life cycle analyses but the data collection and constant monitoring requirements are very different between the two approaches.

A life cycle basis is important for informing environmental regulation because there can be very different and significant impacts in various parts of the supply chain associated with biofuel production. However, whether these regulations can achieve their intended objectives will depend upon development and application of a robust LCA framework for biofuels and successful implementation of the policy.

2.2.2 LCA Challenges for Biofuels

Numerous LCAs for bioethanol and other biofuels have been published (reviews include Fleming et al., 2006; Larson, 2006; and Cheminfo, 2008). Most studies have followed ISO standards (ISO 2006) but wide ranges of results have often been reported for the same fuel pathway, sometimes even when holding temporal and spatial considerations constant. The ranges in results may, in some cases, be attributed to actual differences in the systems being modelled but are also due to differences in method interpretation, assumptions and data issues.

Key issues in biofuels' LCAs have been: differing boundaries being adopted in studies (i.e., what activities are included/excluded from the study), differences in data being collected and utilized, and disparities in the treatment of co-products. In addition, LCAs, more generally (not solely limited to those of biofuels) have often included limited or no analysis of uncertainty and validation of model results. Boundaries in prior LCAs have often differed due to resource constraints. Data requirements in LCA are significant. Studies have not always used up to date data or data that reflected the inputs in the relevant process under study (i.e., utilization of electricity generation data for another jurisdiction rather than the one under study). There are also gaps in scientific knowledge surrounding key variables. For example, these include implications of land use change, N_2O emissions related to feedstock production, and nutrient depletion and erosion due to agricultural residue removal. Utilization of different co-product methods, and in some studies, ignoring co-products entirely, has had major impact on results of LCA studies (Kim and Dale 2002, Larson 2006, Farrell et al. 2006).

Life cycle assessment is a useful tool for comparing on a functional unit basis, the relative environmental performance (based on a specific set of metrics) of different feedstock/fuel pathways. However, LCA should be utilized along with other information in the decision making process regarding biofuel policy development. Decision-makers should be aware of both the strengths and limitations of LCA.

2.3 STRENGTHS AND WEAKNESSES OF LIFE CYCLE ANALYSES

Life cycle assessment is a useful tool for comparing on a functional unit basis, the ***relative*** environmental performance (based on a specific set of metrics) of different feedstock/fuel pathways. However, LCA should be utilized along with other information in the decision making process regarding transportation fuels policy. Decision-makers should be aware of both the strengths and limitations of LCA. In order to more completely understand the implications on the environment (and economy) of fuel production (e.g., scale of production issues, impacts on ecosystem and human health), LCA results should be augmented with those of other modeling systems, economic and market analyses, the judgement of the decision makers, or perhaps, integrated modeling systems could be developed in the future.

Due to the complexity of the systems being modelled, no LCA model can yet perfectly model transportation fuels. GHGenius does have a number of features that make it ideal for undertaking this kind of work, such as a full accounting of land use changes, sensitivity solvers, and the ability to project emissions changes over time.

This work also has limitations. The focus of this work has been to look at the changes in performance of a single system over time. It is not to produce the definitive LCA for biodiesel and thus aspects of the system are simplified or held constant over time in order to better focus on the issue being considered. Another controversial issue with biofuel plants is the subject of indirect land use emissions. There is no accepted methodology, nor verified results for these emissions at this time. Since the interest here is more on the changes in the ***relative*** emissions performance over time any potential indirect effects have not be quantified.

Notwithstanding these limitations, the results of the work are very informative and raise issues for policy makers that have not been thoroughly investigated before.

2.4 GHGENIUS

LCA work involves the collection and utilization of large amounts of data and thus is ideally suited to the use of computer models to assist with the inventorying and analysis of the data. In North America, two models are widely used for the analysis of transportation fuels:

- GREET. A model developed by Argonne National Laboratory in the United States, and
- GHGenius. A model developed by Natural Resources Canada, which has data for both Canada and the United States. This model also has much greater flexibility for modelling different types of crude oil production and many more types of alternative fuels.

Many other LCA models have been developed by governments, universities and the private sector. While all of these models have some small differences in the scope and system boundaries, and may have different emission factors for different regions of the world they would all provide similar results to those developed here, especially when looking at the relative changes over time.

The GHGenius model is used for this work. The model has been developed for Natural Resources Canada over the past eleven years by S&T Squared Consultants Inc. It is based on the 1998 version of Dr. Mark Delucchi's Life Cycle Emissions Model (LEM). GHGenius is capable of analyzing the emissions of many contaminants associated with the production and use of traditional and alternative transportation fuels.

GHGenius is capable of estimating life cycle emissions of the primary greenhouse gases and the criteria pollutants from combustion sources. The specific gases that are included in the model include:

- Carbon dioxide (CO_2),
- Methane (CH_4),
- Nitrous oxide (N_2O),
- Chlorofluorocarbons (CFC-12),
- Hydro fluorocarbons (HFC-134a),
- The CO_2-equivalent of all of the contaminants above.
- Carbon monoxide (CO),
- Nitrogen oxides (NOx),
- Non-methane organic compounds (NMOCs), weighted by their ozone forming potential,
- Sulphur dioxide (SO_2),
- Total particulate matter.

The model is capable of analyzing the emissions from conventional and alternative fuelled internal combustion engines or fuel cells for light duty vehicles, for class 3-7 medium-duty trucks, for class 8 heavy-duty trucks, for urban buses and for a combination of buses and trucks, and for light duty battery powered electric vehicles. There are over 200 vehicle and fuel combinations possible with the model.

GHGenius can predict emissions for past, present and future years through to 2050 using historical data or correlations for changes in energy and process parameters with time that are stored in the model. The fuel cycle segments considered in the model are as follows:

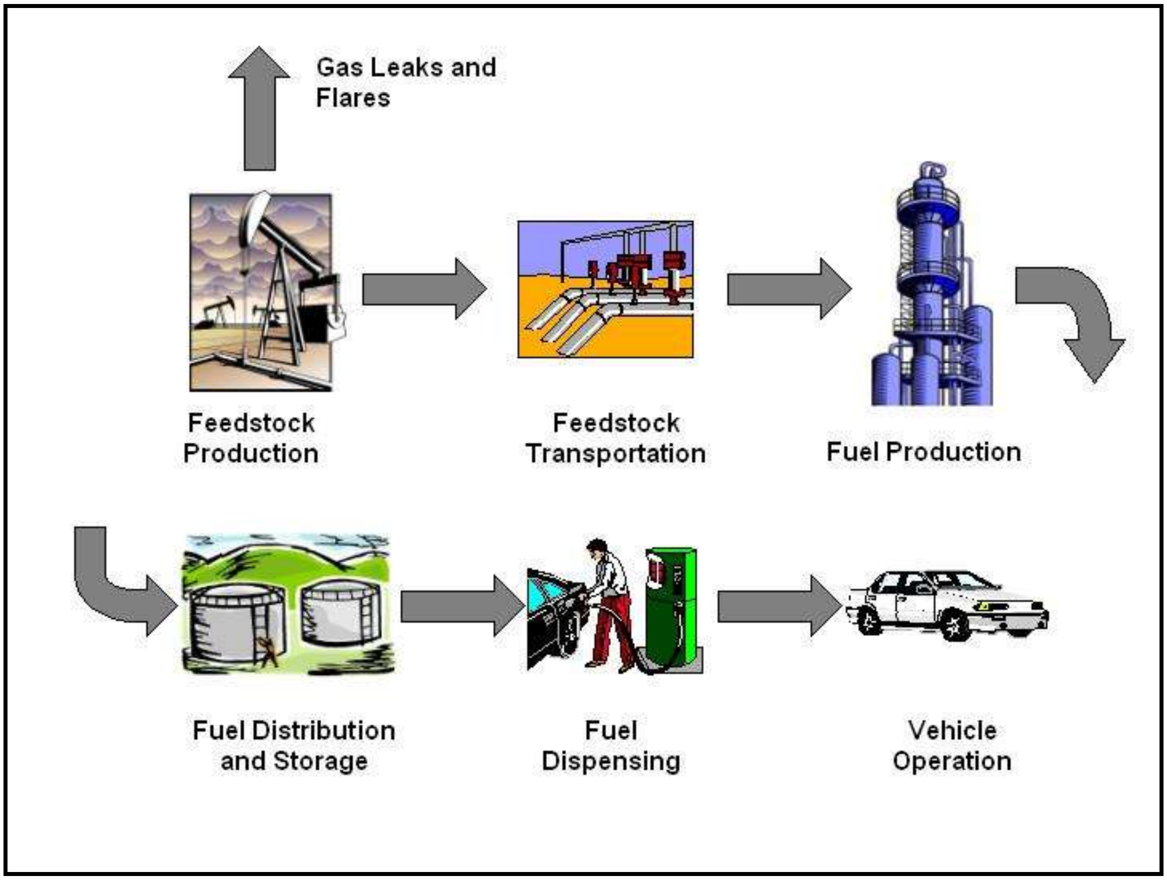
- Vehicle Operation

Emissions associated with the use of the fuel in the vehicle. Includes all greenhouse gases.

- Fuel Dispensing at the Retail Level
  Emissions associated with the transfer of the fuel at a service station from storage into the vehicles. Includes electricity for pumping, fugitive emissions and spills.
- Fuel Storage and Distribution at all Stages
  Emissions associated with storage and handling of fuel products at terminals, bulk plants and service stations. Includes storage emissions, electricity for pumping, space heating and lighting.
- Fuel Production (as in production from raw materials)
  Direct and indirect emissions associated with conversion of the feedstock into a saleable fuel product. Includes process emissions, combustion emissions for process heat/steam, electricity generation, fugitive emissions and emissions from the life cycle of chemicals used for fuel production cycles.
- Feedstock Transport
  Direct and indirect emissions from transport of feedstock, including pumping, compression, leaks, fugitive emissions, and transportation from point of origin to the fuel refining plant. Import/export, transport distances and the modes of transport are considered.
- Feedstock Production and Recovery
  Direct and indirect emissions from recovery and processing of the raw feedstock, including fugitive emissions from storage, handling, upstream processing prior to transmission, and mining.
- Fertilizer Manufacture
  Direct and indirect life cycle emissions from fertilizers, and pesticides used for feedstock production, including raw material recovery, transport and manufacturing of chemicals. This is not included if there is no fertilizer associated with the fuel pathway.
- Land use changes and cultivation associated with biomass derived fuels
  Emissions associated with the change in the land use in cultivation of crops, including N_2O from application of fertilizer, changes in soil carbon and biomass, methane emissions from soil and energy used for land cultivation.
- Carbon in Fuel from Air
  Carbon dioxide emissions credit arising from use of a renewable carbon source that obtains carbon from the air.
- Leaks and flaring of greenhouse gases associated with production of oil and gas
  Fugitive hydrocarbon emissions and flaring emissions associated with oil and gas production.
- Emissions displaced by co-products of alternative fuels
  Emissions displaced by co-products of various pathways. System expansion is used to determine displacement ratios for co-products from biomass pathways.
- Vehicle assembly and transport
  Emissions associated with the manufacture and transport of the vehicle to the point of sale, amortized over the life of the vehicle.
- Materials used in the vehicles
  Emissions from the manufacture of the materials used to manufacture the vehicle, amortized over the life of the vehicle. Includes lube oil production and losses from air conditioning systems.

The stages of the "wells to wheels" lifecycle of traditional fossil fuels captured by GHGenius are shown in the following figure. GHGenius version 3.19 is used for this work. All GHGenius results are presented on the basis of the Higher Heating Value of the fuels unless otherwise specified.

Figure 2-3 GHGenius Life Cycle Stages



The foundation of all LCA work is the process data that is used to develop the results. In the following three sections data is presented for feedstock production, oil extraction and biodiesel production for rapeseed/canola and soybeans. Data has been collected for a number of regions and in some cases time series of data are available. This data will form the basis of the analysis of how emissions have changed over time, of identifying regional differences, and the comparison of model results. Sections 3, 4, and 5 of this report document the input parameters for all stages of the biodiesel production cycle for rapeseed and soybeans in different geographic areas and the trends for many of these parameters.

3. FEEDSTOCK PRODUCTION

For most biodiesel production systems the emissions from the production of the feedstocks contribute the majority of the lifecycle emissions. Feedstock emissions are dependent on the feedstock characteristics, location, agronomic processes, climate and other factors and thus one would expect that emissions would vary not only with the crop but also on where and how the crop is produced. This section documents some of these issues with respect to two feedstock families, rapeseed (or canola) and soybeans.

3.1 RAPESEED OR CANOLA

Rapeseed (Brassica napus), also known as rape, oilseed rape, rapa, rappi, rapaseed (and in the case of one particular group of cultivars, canola) is a bright yellow flowering member of the family Brassicaceae (mustard or cabbage family). Canola is the name given to certain varieties of oilseed rape, or the oil produced from those varieties. Canola is a trademark for a hybrid variety of rape initially bred in Canada ("canola" being an acronym for Canadian oil, low acid). Canola has been bred to reduce the amount of glucosinolates, yielding a more palatable oil. This has had the side-effect that the oil contains much less erucic acid.

Rapeseed is grown for the production of animal feed, vegetable oil for human consumption, and biodiesel; leading producers include the European Union, Canada, the United States, Australia, China and India. Rapeseed/canola is the third leading source of vegetable oil in the world, after soybean and oil palm, and also the world's second leading source of protein meal, although only one-fifth of the production of the leading soybean meal[1].

Table 3-1 World Vegetable Oil Production

	2005/06	2006/07	2007/08	2008/09	2009/10
Production	Million tonnes				
Oil Palm	35.8	37.3	41.0	43.9	45.0
Oil Soybean	34.8	36.3	37.6	35.7	38.7
Oil Rapeseed	17.3	17.1	18.4	20.5	22.3
Oil Sunflowerseed	10.6	10.6	9.9	11.9	11.5
Oil Palm Kernel	4.4	4.4	4.9	5.1	5.4
Oil Cottonseed	4.9	5.1	5.2	4.8	4.7
Oil Peanut	5.0	4.5	4.9	5.0	4.7
Oil Coconut	3.5	3.2	3.5	3.5	3.6
Oil Olive	2.7	2.9	2.8	3.0	2.9
Total	118.8	121.6	128.2	133.4	138.6

---

[1] USDA Production Supply and Disposition. http://www.fas.usda.gov/psdonline/psdHome.aspx

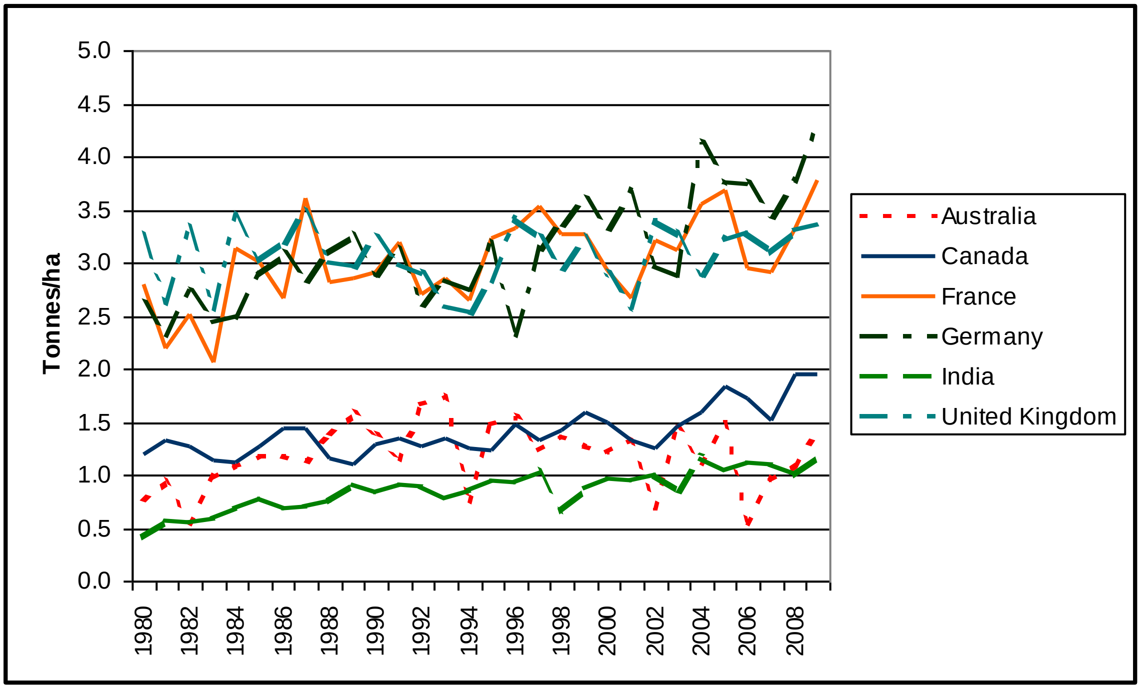
Table 3-2 World Oilseed Meal Production

	2005/06	2006/07	2007/08	2008/09	2009/10
Production	Million tonnes				
Meal Soybean	146.6	153.8	158.5	151.4	164.8
Meal Rapeseed	26.6	25.9	27.6	30.8	33.6
Meal Cottonseed	14.6	15.3	15.6	14.4	14.0
Meal Sunflowerseed	11.5	11.5	10.6	12.8	12.4
Meal Palm Kernel	5.2	5.3	5.8	6.1	6.3
Meal Peanut	6.0	5.5	5.9	6.1	5.6
Meal Fish	5.0	5.1	5.2	5.1	4.5
Meal Copra	1.8	1.7	1.9	1.9	1.9
Total	217.1	224.0	231.2	228.5	243.1

3.1.1 Yield

The yields of rapeseed vary significantly from region to region but all of the major producers have been experiencing increases in yield over time. This information is shown in the following figure[2].

Figure 3-1 Rapeseed Yield



The availability of moisture has a large impact on the crop yield, with Canada and Australia being moisture limited. France, Germany and the UK plant mostly winter rapeseed, whereas

---

[2] FAOStats. http://faostat.fao.org/site/567/default.aspx#ancor

in Canada the winter temperatures are too low for the plants to survive and the crops can't take advantage of the winter and early spring moisture.

The yield of a crop has a small impact on the GHG emissions per unit of energy produced from the production of the crop since only a small portion of the production activities are area related and mostly independent of yield (e.g. direct fuel use for tractors). Fertilizer use tends to be a function of the quantity of the crop produced and thus high yield regions will use more fertilizer in total but not necessarily more per unit of production. If the GHG emissions are presented on the basis of a different function unit, such as per unit of area farmed, then the GHG could be sensitive to crop yield.

3.1.2 Fertilizer

Rapeseed requires significant quantities of nitrogen fertilizer since it does not fix its own nitrogen as soybeans do. The quantity of fertilizer used has a large impact on the GHG emissions from producing rapeseed since the nitrogen fertilizer production process is very emissions intensive.

3.1.2.1 Europe

An EU project called IRENA, undertaken by the European Environmental Agency a decade ago, identifies a number of environmental indicators for agriculture. As part of this project the nitrogen and phosphorus fertilizer application rates per crop were identified for each of the EU-15 countries. This information is shown in the following table along with the yield, so that the rates can be shown both on a per hectare basis and a per tonne basis.

Table 3-3 Rapeseed Fertilizer Rates

	UK	France	Germany
Rapeseed yield (1999-2001 avg.)	2.89	2.95	3.52
N applied, kg/ha	190	145	170
N applied, kg/tonne	65.7	49.2	48.3
P_2O_5 applied, kg/ha	41	42	45
P_2O_5 applied, kg/tonne	14.2	14.2	12.8

3.1.2.2 Canada

In Canada, a major survey of 650 western Canadian canola growers was undertaken in October/November 2000 (Canola Council, 2001). The study was designed to compare transgenic canola to conventional canola. About 90% of the canola produced in Canada is now genetically modified. The survey collected data on yield, fertilizer application and other production practices. The fertilizer results are summarized in the following table.

Table 3-4 Canadian Canola Fertilizer Survey Data - 2000

		Transgenic	Conventional
Yield	Tonnes/ha	1.64	1.49
Seeds	kg/tonne	4.0	4.6
N	kg/tonne	48.7	53.5
P_2O_5	kg/tonne	17.1	19.0
K_2O	kg/tonne	4.0	3.7
S	kg/tonne	8.4	8.9

In spite of the yields being about two times higher in Germany and France, the nitrogen application rates per tonne of rapeseed produced are essentially the same in North America and Europe. The two data sets were collected during the same time period.

3.1.2.3 Fertilizer Trends

Information on fertilizer trends for rapeseed is difficult to obtain but the total of each of the fertilizers applied per hectare and per tonne of agricultural products produced can be extracted from the FAO statistical database. Information is shown for Germany, France, and the UK for each of the three primary fertilizers in the following figures.

Figure 3-2 Nitrogen Trends per Hectare

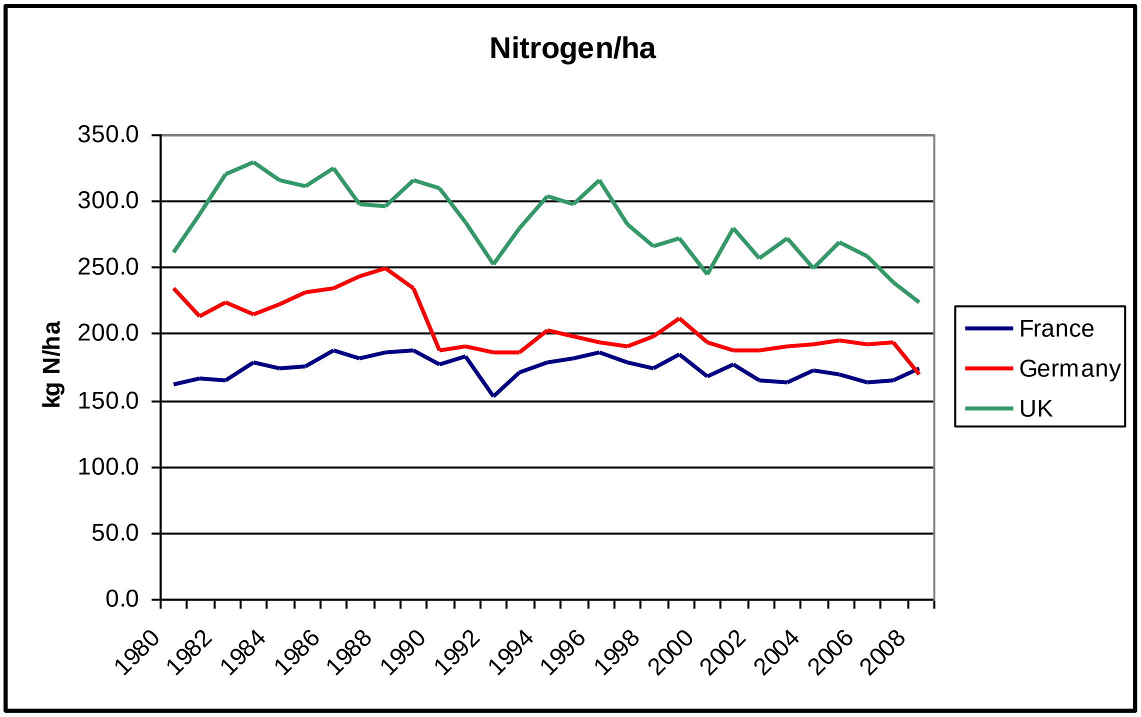


Figure 3-3 Nitrogen Trends per Tonne Produced

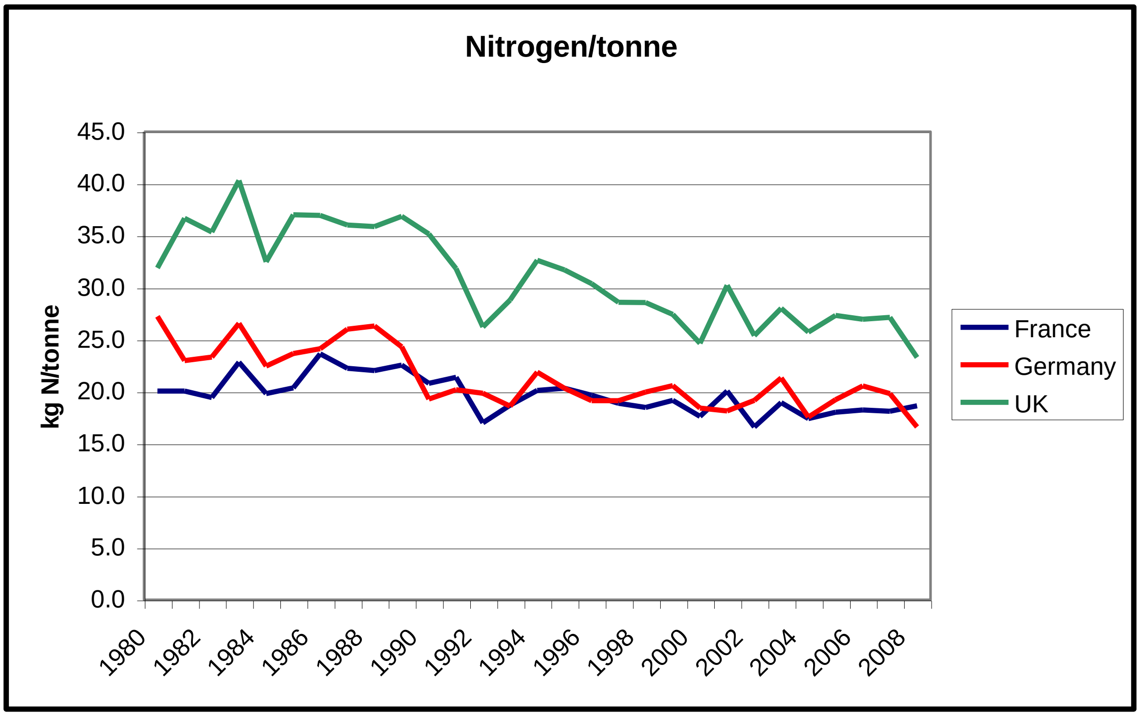


Figure 3-4 Phosphorus Trends per Hectare

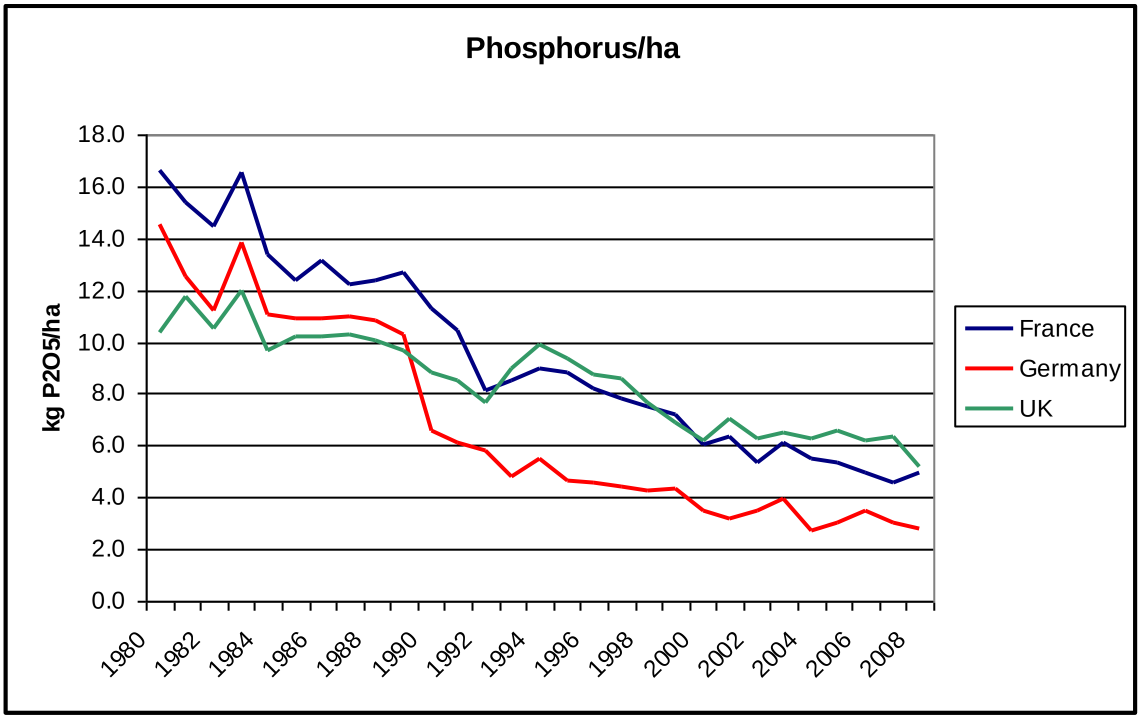


Figure 3-5 Phosphorus Trends per Tonne

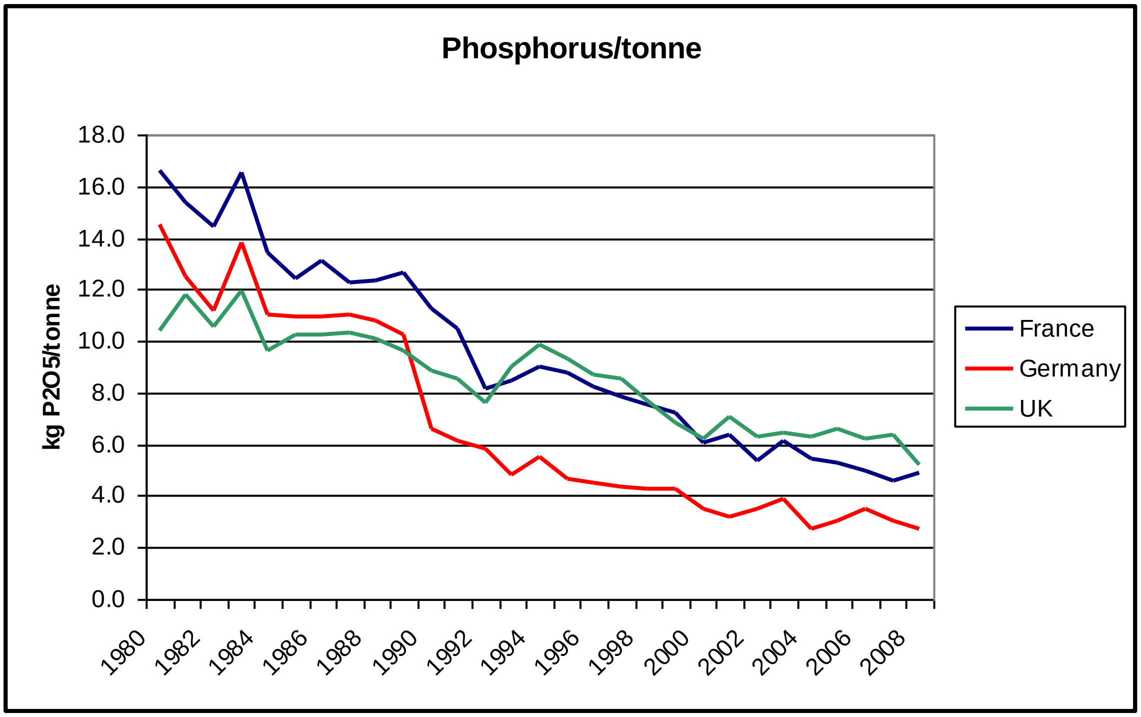


Figure 3-6 Potash Trends per Hectare

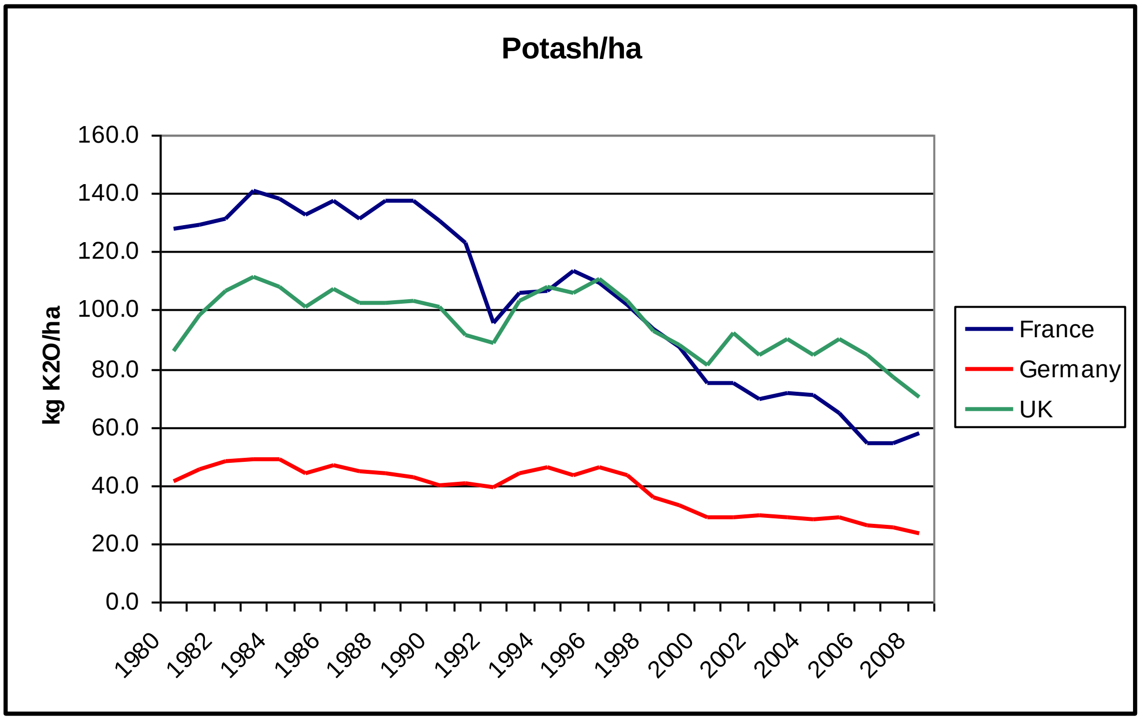
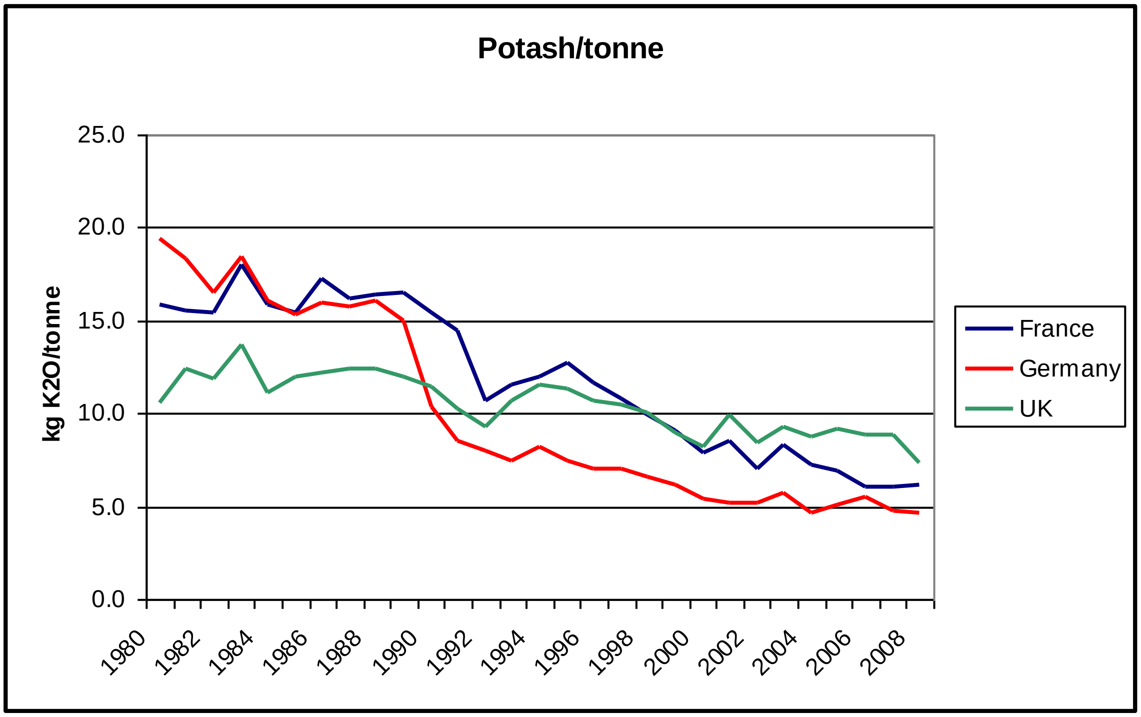


Figure 3-7 Potash Trends per Tonne



This data shows improving trends in fertilizer efficiency during a period where rapeseed production was increasing both in terms of area cultivated and fraction of the total crop produced as shown in the following figures.

Figure 3-8 Rapeseed as % of Cultivated Area

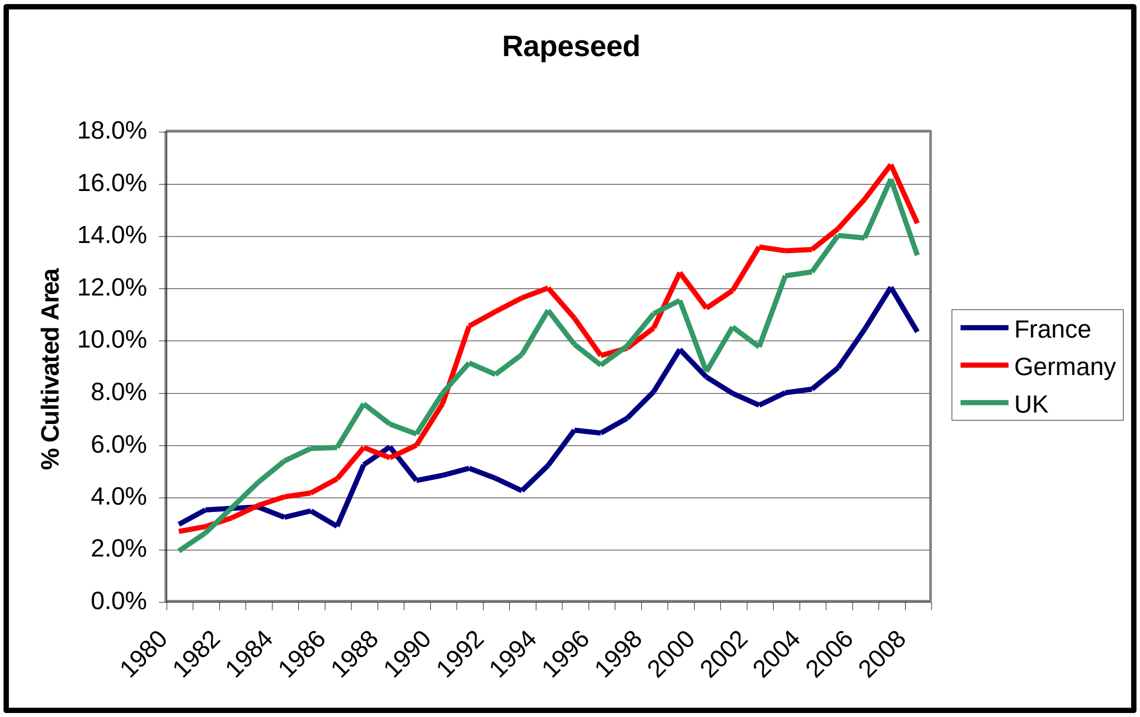
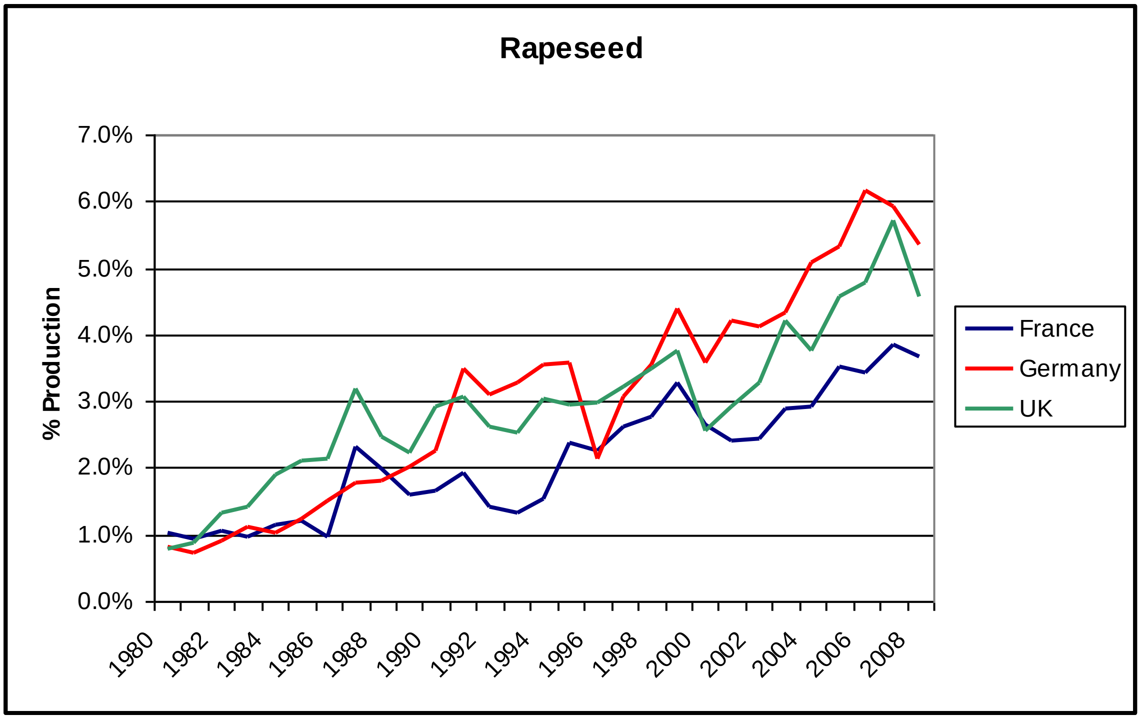
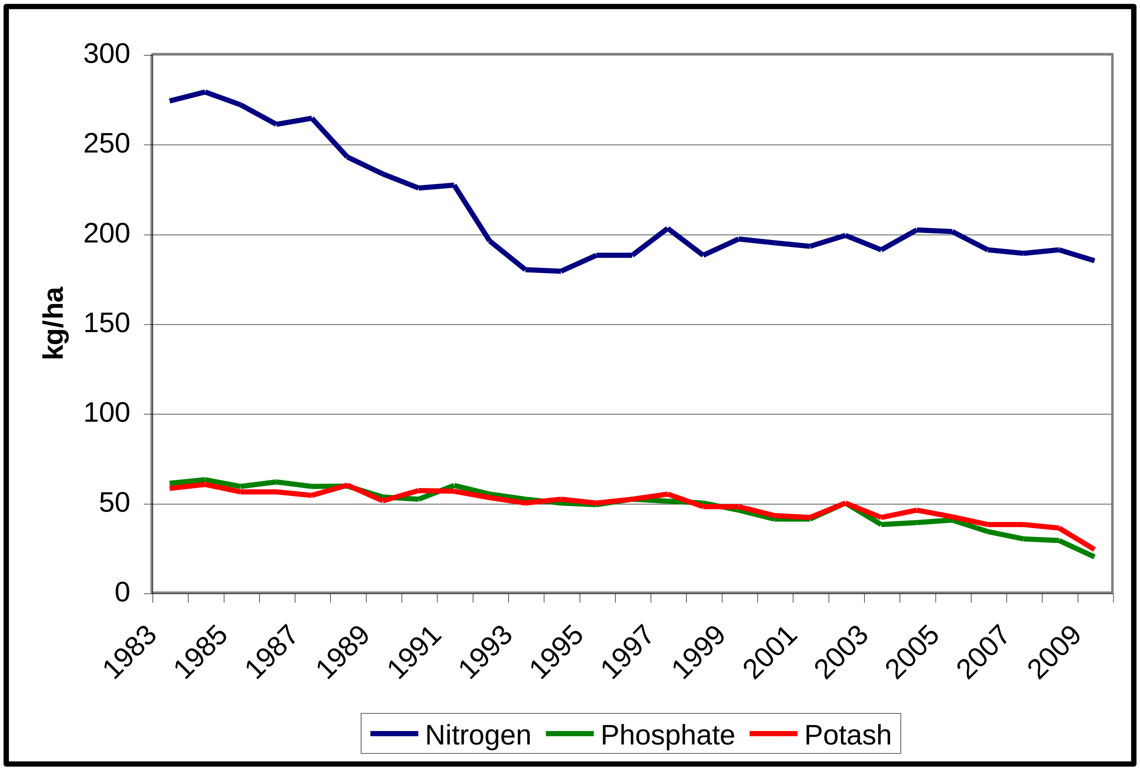


Figure 3-9 Rapeseed as % of Crop Production



All of the above figures indicate that fertilizer application rates have been declining for all crops combined. The following figure is specifically for rapeseed in the UK and shows similar trends (Defra, 2010).

Figure 3-10 UK Fertilizer Trends Rapeseed



3.1.3 Direct Energy

Good quality data on farm energy use at the crop level is always difficult to obtain as most producers will grow more than one crop and do not allocate their energy purchases between crops. The IRENA data on energy consumption calculates both the direct energy use and the indirect energy use in fertilizers. The total energy use is reported to be 6 to 7 GJ/ha between 1990 and 2000, and in some countries it increased, while in other countries it decreased. Fuel use is reported to about 50%, with some countries reporting some energy used for heating. Fertilizer energy use is reported to be about 35% of the total. This would indicate that field energy is in the range of 3 to 4 GJ/ha.

3.1.3.1 Europe

There is some limited data available from field trials, research studies and government reports on fuel use for rapeseed production in Europe. These include the following reports.

- A study by Moerschener and Lucke (2002) reported the energy and fertilizer requirements for various crops on two sites in Germany. This information is shown below for the conventional farming systems. The conversion of MJ to litres includes the energy required to produce the diesel fuel as well as the energy embedded in the fuel.

Table 3-5 Cultivation Energy German Rapeseed

	Primary Energy	
	MJ/ha	Litres/ha
Reinshof (1990-94)	2,991	74
(1995-98)	2,925	72
Marienstein (1990-94)	2,711	67
(1995-98)	2,713	67

- A report by Unilever (2007) on the sustainability of winter rapeseed production reported fossil fuel use ranging from 3.3 to 3.7 GJ/ha (75 to 94 litres diesel fuel/ha). This is slightly higher than the field trials shown in the previous table.
- Bernesson (2004) reported on calculations for fuel consumption for winter rapeseed production in Sweden and found that 63.4 l/ha of diesel fuel was required.
- HGCA (2005) reported primary energy use for oilseed rape as 2.647 GJ/ha in the UK. This is 67 l/ha. HGCA is the cereals and oilseeds division of the Agriculture and Horticulture Development Board (AHDB).

The other sources of information are the values used in the LCA work that has been done in Europe. These are summarized in the following table.

Table 3-6 Direct Field Energy – Rapeseed

Source	Value	Reference
	L/ha	
JRC	71	Multiple German sources
UK Carbon Tool	66	Mortimer et al (2003). From Kaltschmidtt and Reinhardt 1997 (IFEU).
Dutch Carbon Calculator	66-112	Mortimer and PAV (2000)
Germany default value	66	Calculation by IFEU

Other than one Dutch value (112 l/ha) all of the other values can be traced back to various sources in Germany with the UK and German values having the same source. The fuel consumption per tonne of production is in the range of 22 to 32 l/tonne.

3.1.3.2 Canada

The field energy requirements for growing canola in Canada have never been surveyed on a regular basis, as were the fuel energy requirements for corn and soybeans in the United States. Agriculture and Agri-Food Canada (2001) did a significant amount of analysis on the opportunities to reduce energy use in agriculture throughout the 1990s.

Crop inputs, field operations (use of farm machinery) and yield data from field experiments conducted by AAFC Research Centres and the University of Manitoba were used for the micro-level analysis (Agriculture and Agri-Food Canada, 1999). Several sites and four soil zones were used in the micro-level analysis:

- Swift Current, SK for the Brown soil zone
- Lethbridge, AB and Scott, SK for the Dark Brown soil zone
- Melfort, SK, Indian Head, SK and Glenlea, MB for the Black soil zone
- Tisdale, SK and Rycroft, AB for the Gray soil zone.

The micro-level data were scaled to the farm level using representative farms typical of the soil zones within each province. This scaled data was obtained for canola from the original researchers (Nagy, 2010). The field energy data was extracted from the information and the summary is presented in the following table. All of the data was collected before the development of transgenic canola. The benefits of no till practices are much lower in this data set than in most other descriptions of the benefits of no-till.

Table 3-7 Field Energy Requirements Canola

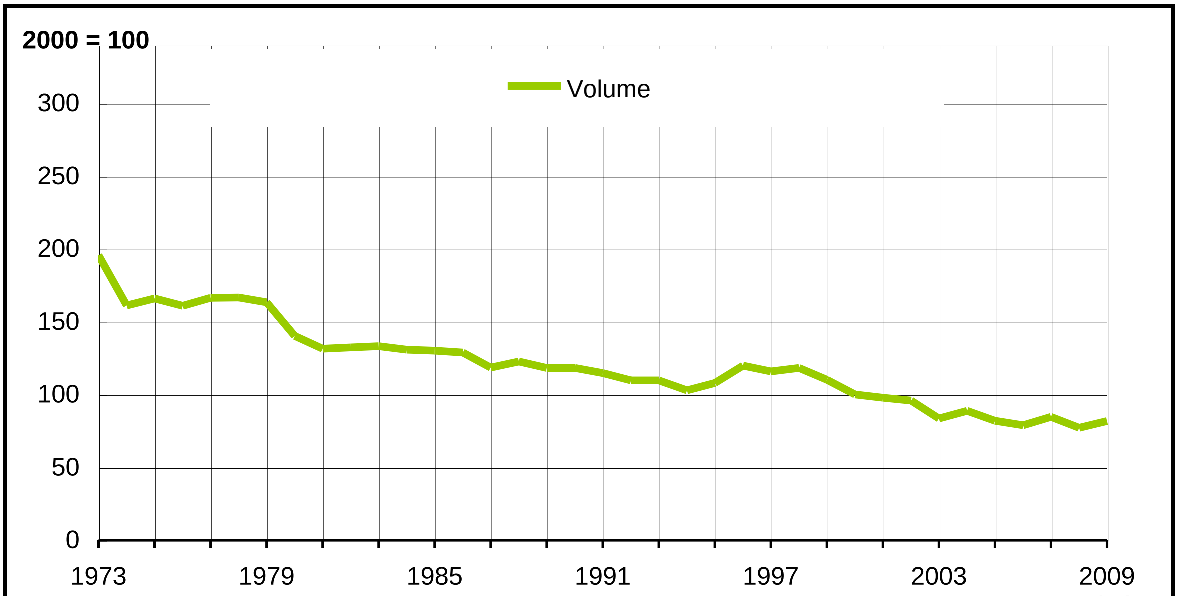
	Percentage of Canola Production	Full Tillage	No Tillage
		L diesel fuel equivalent/ha	
Manitoba	20%	43.0	37.1
Saskatchewan	45%	39.8	34.8
Alberta	25%	40.4	35.1
Weighted Average		36.6	31.9

The GHGenius fuel is input on the basis of fuel/tonne produced and not per hectare. Using 1994 as the base year, and 35 l/ha as an average of the fuel consumed, the default input value is 28.2 l/tonne. This is in the middle of the European range but both the numerator and the denominator are very different and reflect the very different cultivation methods employed and the different growing conditions.

3.1.3.3 Direct Energy Trends

On a per unit of production basis, the energy requirements will decline as yield increases if the total direct energy per hectare is constant. The following figure shows the change in energy efficiency in the UK over the past 40 years for all of agriculture.

Figure 3-11 Energy Use Efficiency - UK



Source: Defra Statistics

3.1.4 Other Agricultural Chemicals

The use of lime for soil pH control and pesticides are two other important groups of agricultural chemicals used for rapeseed production.

3.1.4.1 Europe

In terms of pesticide application rates, the Moerschner study found 2.9 to 3.3 kg active ingredient/ha were applied. The Unilever study had a mean value of about 10 kg/ha. Both of these values are very high and much higher than the values reported in the UK bi-annual survey. The values in the various LCA tools are summarized in the following table.

Table 3-8 Pesticide Application Rates – Rapeseed

Source	Value	Reference
	Kg ai/ha	
JRC	1.23	Multiple German sources
UK Carbon Tool	0.28	British Pesticide Use Survey
Germany default value	1.23	Calculation by IFEU

The information on lime usage in the various LCA tools is summarized in the following table. There is considerable variation between tools.

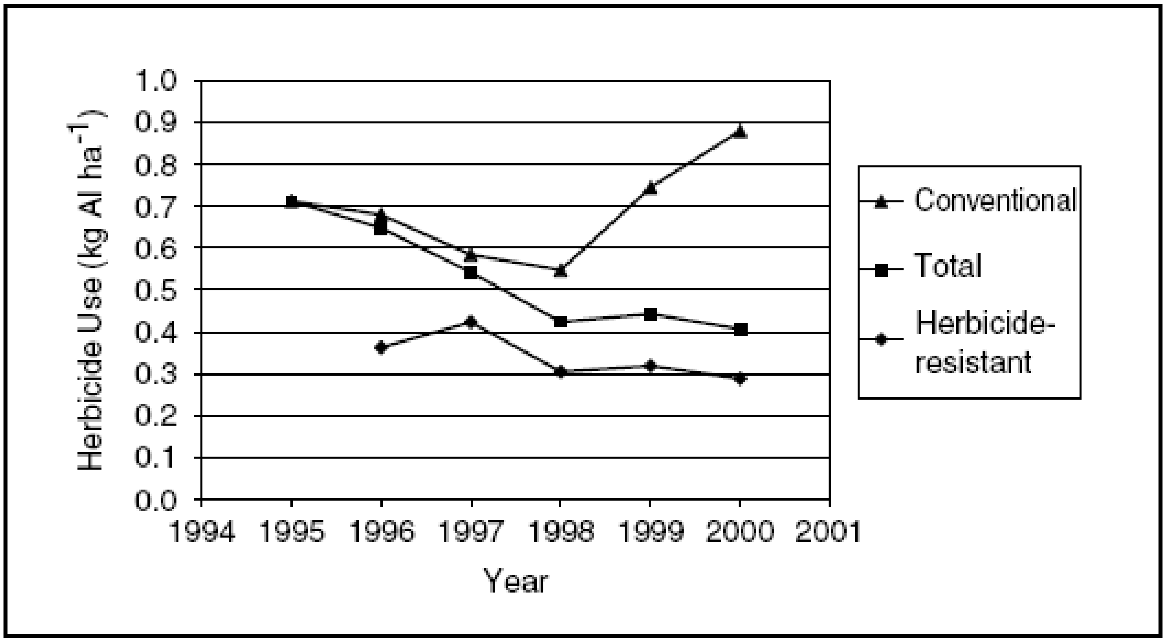
Table 3-9 Lime Application Rates – Rapeseed

Source	Value	Reference
	kg/ha	
JRC	19	European Fertiliser Manufacturer Association (EFMA), 2008. JRC.
UK Carbon Tool	271	Mortimer et al (2003). From Kaltschmidtt and Reinhardt 1997 (IFEU).
Germany default value	22	Calculation by IFEU

3.1.4.2 Canada

Herbicide use for canola in Canada was analyzed by Brimmer et al (2005). It was found that the active ingredient application rate was declining and it varied between conventional and genetically modified seeds. A summary figure from that publication is shown in the following figure. The application rate was 0.3 litres a.i./hectare for the genetically modified crop and 0.9 l a.i./ha for the conventional seed. The default value in GHGenius is a conservative 0.8 kg a.i./tonne of canola produced.

Figure 3-12 Herbicide Use Canola 1995-2000



Lime is rarely used in western Canada due to the alkaline nature of most of the soils. No data is available for lime use for canola production but the total area that is limed in each province is available in the 2006 Census of Agriculture (Statistics Canada). A comparison of area prepared for seed to area limed is shown in the following table. No lime is assumed for canola production.

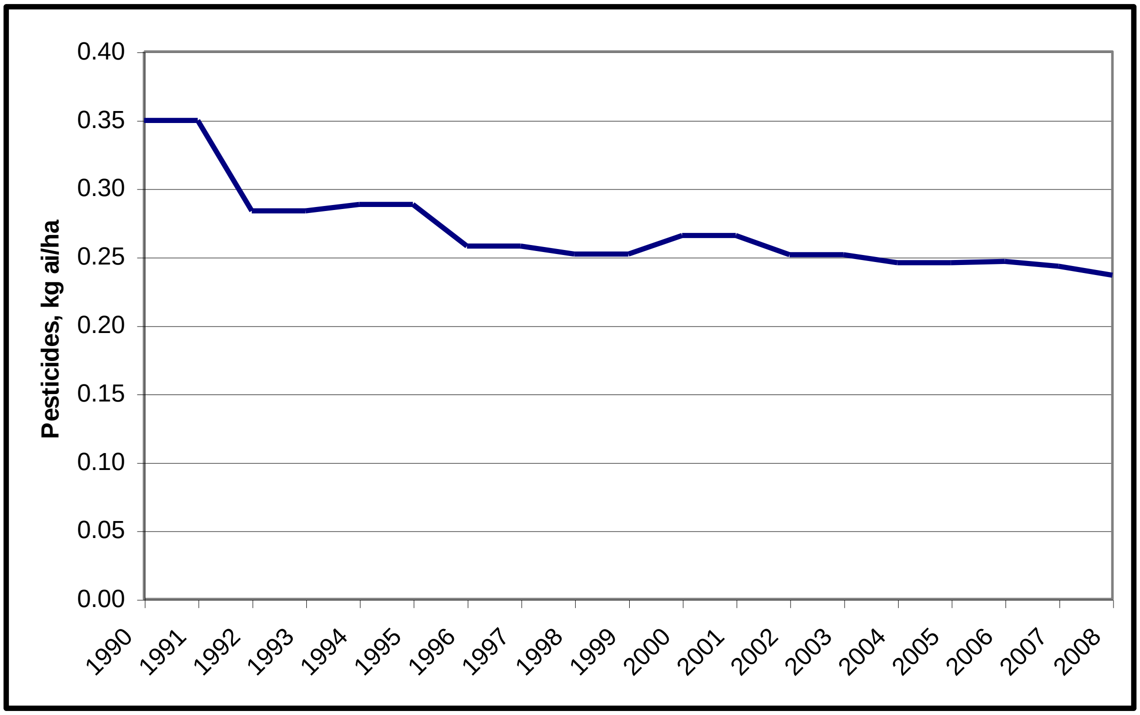
Table 3-10 Lime Area in Western Canada

	Seeded Area	Limed Area	% Limed Area
	hectares		
Manitoba	3,890,618	17,883	0.46
Saskatchewan	13,348,192	54,265	0.41
Alberta	7,578,201	12,117	0.16
Total	24,817,011	84,265	0.34

3.1.4.3 Pesticide Trends

The application rates in the UK for oilseed rape are shown in the following figure (The Food and Environmental Research Agency). The data is from a biannual survey of producers. A reduction in application rates over time can be observed.

Figure 3-13 Pesticide Application Rates UK Oilseed Rape



3.1.5 Soil Carbon Changes

The cultivation of the soil can lead to soil carbon changes and this source of emissions is often overlooked in many LCA determination of biofuels. The magnitude of the emissions is dependent on the soil type and management practices, which differ significantly in different regions.

3.1.5.1 Europe

Data on soil carbon changes for European countries is not always reported in their UNFCCC National Inventory Reports. Germany reports a small loss of carbon of 0.002 t CO_2eq/ha for cropland remaining cropland. The UK reports a loss of 0.051 t CO_2eq/ha for cropland remaining cropland.

3.1.5.2 Canada

Canola is grown in western Canada, where the management practices have changed from primarily conventional tillage (often with a fallow year in the crop rotation) to one of continuous cropping and direct seeding (no tillage). As a result of this, soil carbon content has been increasing in recent years. The rate of change is estimated to be 0.30 t CO_2eq/ha for canola production (McConkey et al, 2010).

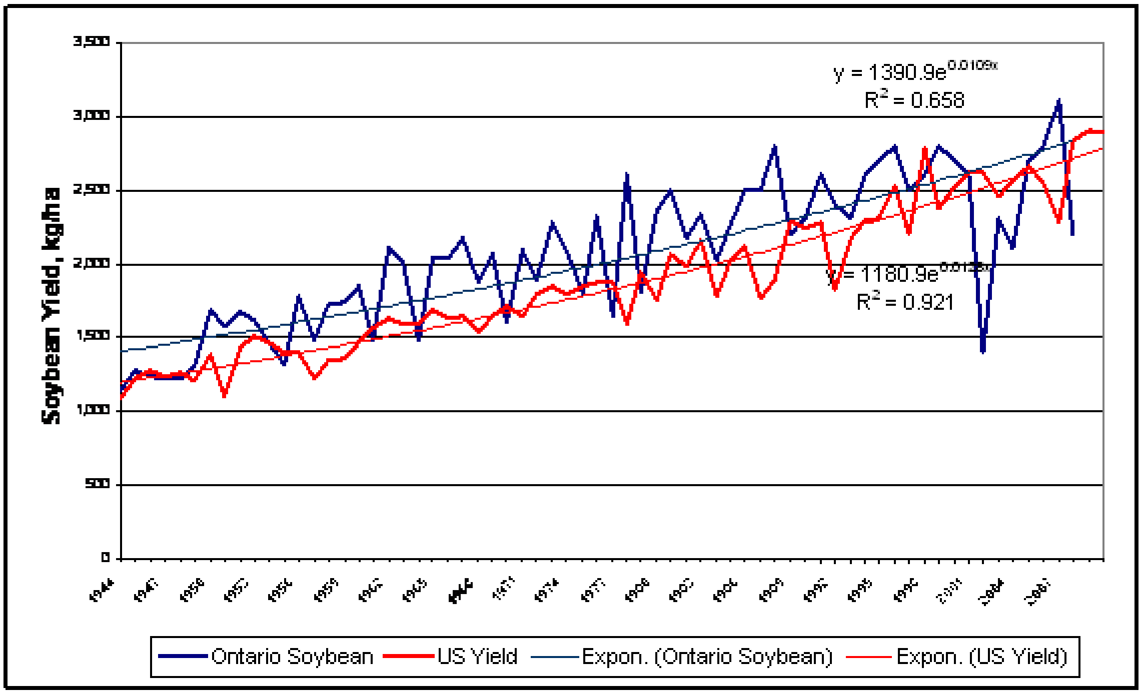
3.2 SOYBEANS

Soybeans are the major oilseed crop produced in the United States and the second largest in Canada. They are also an important oilseed crop in South America. Soyoil is widely used for biodiesel production in the United States and in some South American countries.

3.2.1 Yield

Long term soybean yield information for Canada and the United States is shown in the following figure. The Canadian data is from Statistics Canada, (Cansim table 001-0010), and the US data is from the USDA, (National Agricultural Statistics Service).

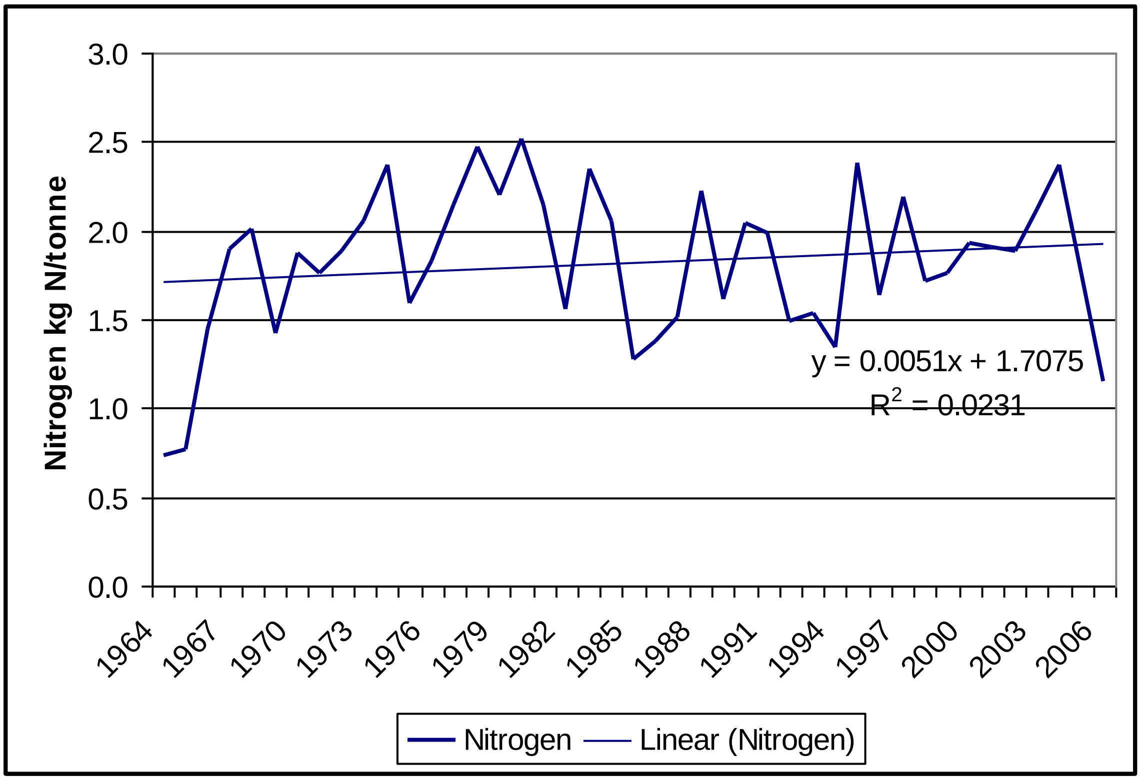
Figure 3-14 Soybean Yield



3.2.2 Fertilizer

The USDA data for fertilizer use for soybeans in the US is shown in the following figures. In theory, soybeans do not require any nitrogen as they fix their own nitrogen from the atmosphere but in practice a small amount of nitrogen fertilizer is used to start the plant. While the trend line shows a small increase over the past 40 years, the most recent data shows no trend. This no trend assumption is now used in GHGenius and the default value is 1.70 kg/tonne of soybeans.

Figure 3-15 Soybean Nitrogen Use



The phosphorous and potassium fertilizer application rates are shown in the following figure. Both data series show relatively flat trend lines over the entire period but a decline in fertilizer application in recent years.

Figure 3-16 Soybean Phosphorus Use

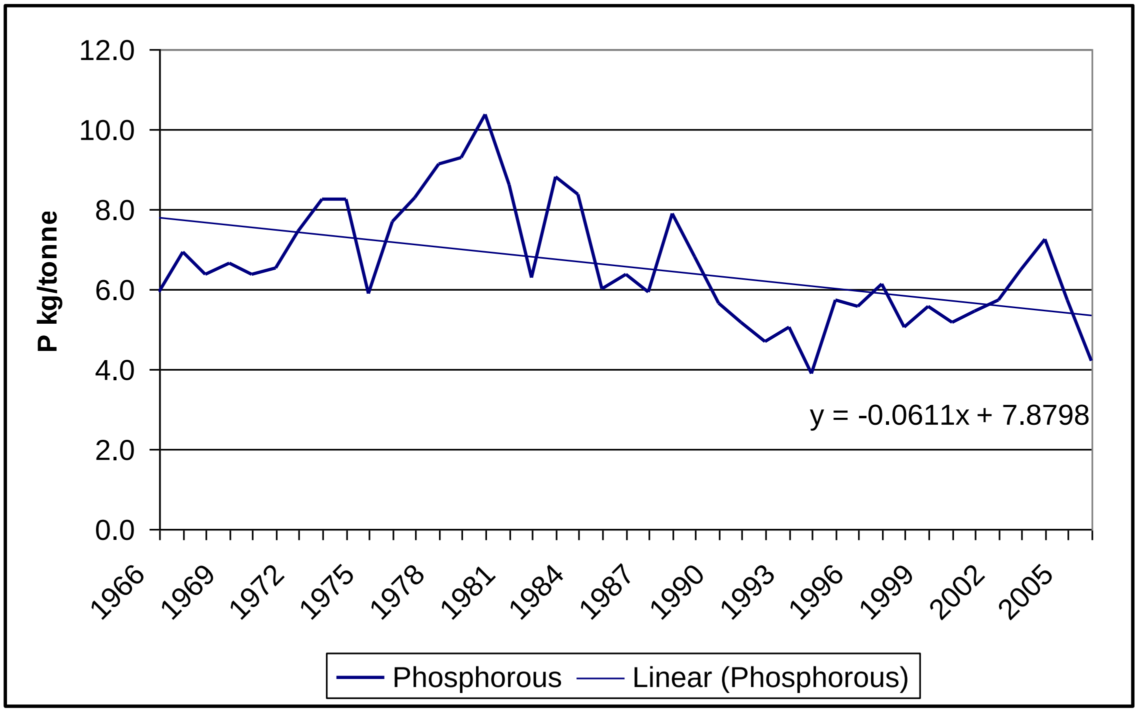
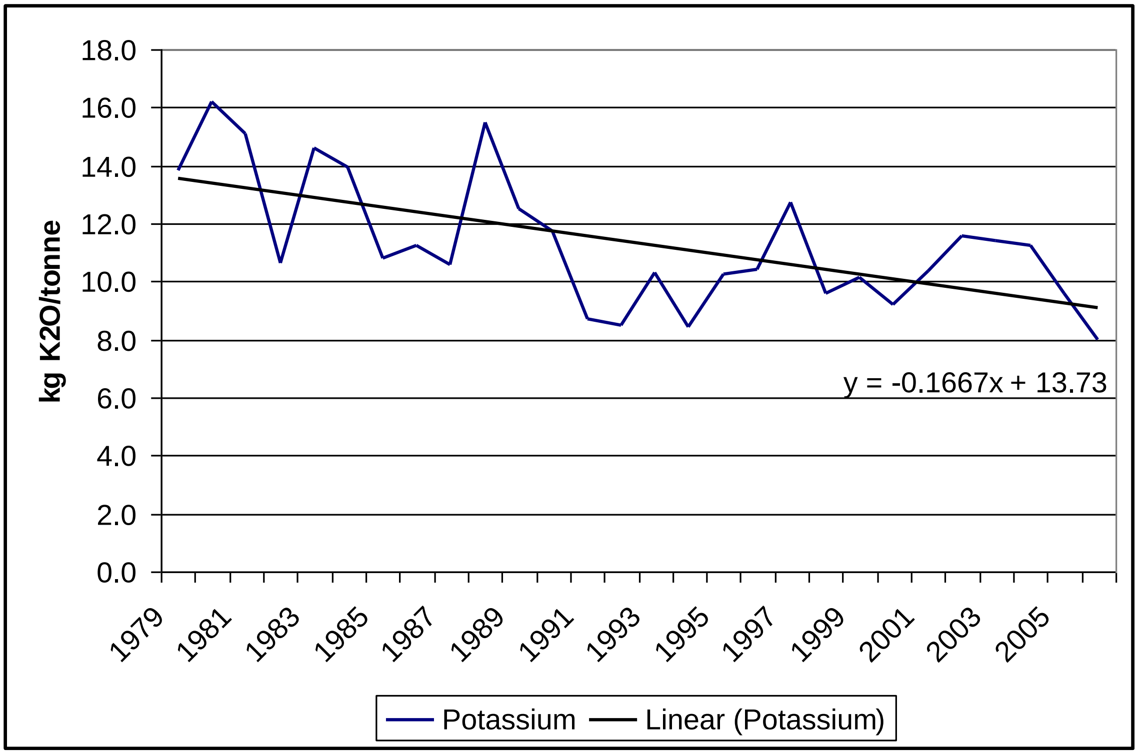


Figure 3-17 Soybean Potassium Use



The values that will be used in GHGenius are summarized in the following table.

Table 3-11 Soybean Input Parameter Summary

	Canada 2010
	kg/tonne
Harvest Yield, t/ha	2.85
P_2O_5	5.44
K_2O	8.82
Sulphur	1.23
Pesticides	0.51
Seeds	41.67
Nitrogen	1.79
Manure	0.0

3.2.3 Direct Energy

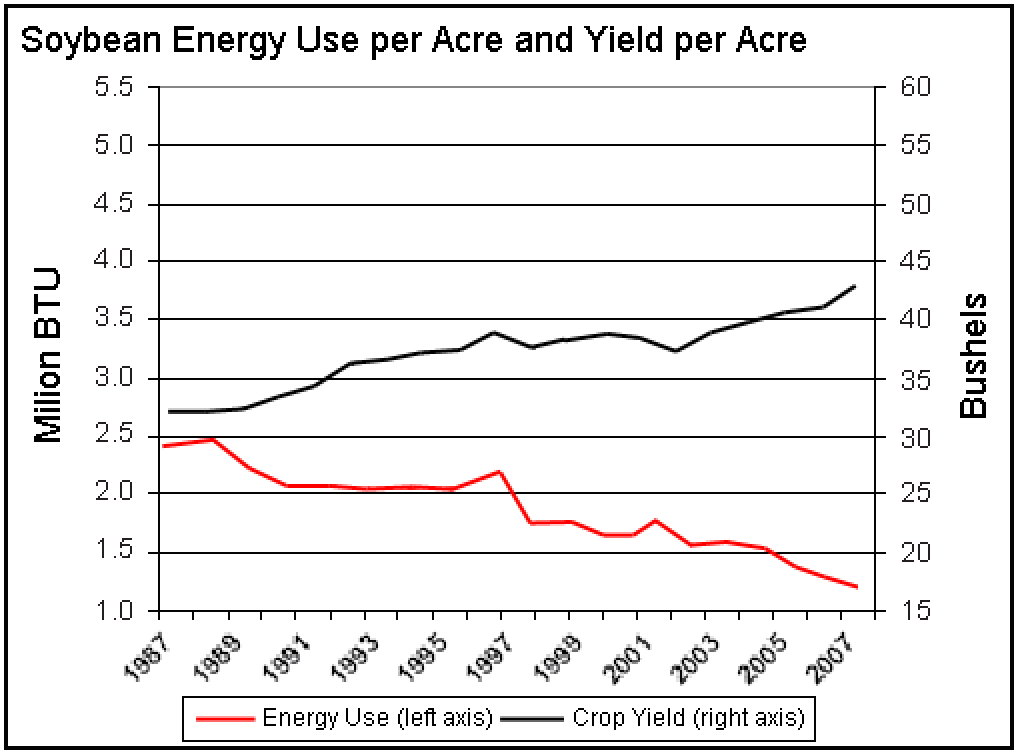
The energy requirements for soybeans produced in the United States in 2002 are reported by the USDA (2004b). This data has been converted to a per tonne basis in the following table.

Table 3-12 Soybean Production - Fuel Use

	Canada 2010
	Per tonne
Diesel, L	12.27
Natural Gas, L	1,176
Electricity, kWh	6.18
Gasoline, L	3.87
LPG, L	1.31
Total energy, kj	708,784

The total energy used for producing soybeans in the United States has been reported by The Keystone Center, as part of the Field to Market Program. The total energy use includes the direct fuel use and the energy embedded in the fertilizer. Those results are shown in the following figure. The trend to lower energy use per unit of production is apparent.

Figure 3-18 Energy use in Soybean Production – United States

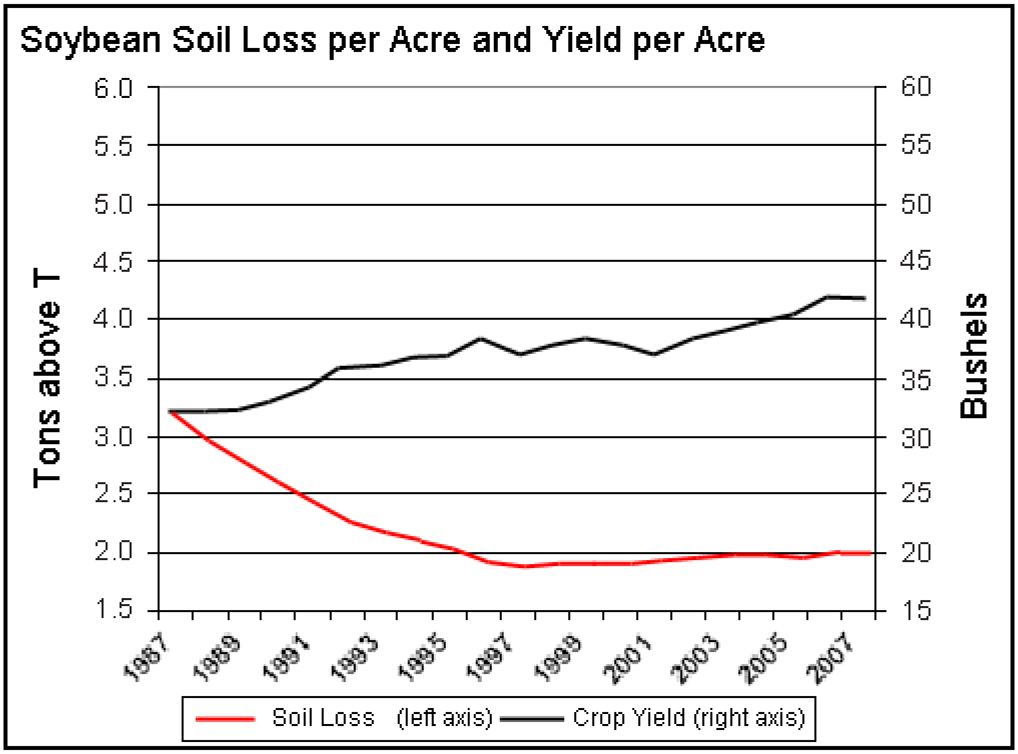


3.2.4 Soil Carbon Changes

The United States reports that soil carbon stocks are increasing for the total of all agricultural land in the US. This category includes land in conservation reserve programs and land in perennial crops.

The Field to Market results for soybeans are shown in the following figure. It can be seen that after about 1997, soil carbon has been stabilized and is showing some signs of increasing.

Figure 3-19 Soybean Soil Loss



In Canada, the majority of soybeans are grown in a region where the soil carbon content of the soil is still declining at a rate of about 0.75 t CO_2eq/ha (McConkey et al).

3.3 SUMMARY

Feedstock production practices for rapeseed/canola and soybeans have been investigated in different regions of North America and Europe. There is a significant variation in some practices but also some similarities in other practices. The data that is available is clear that the efficiency and productivity of feedstock production has improved significantly in the past several decades.

Perfect data sets that can be used to assess the GHG emissions of feedstock production in any one country does not currently exist but sufficient data is available that it should be possible to investigate the GHG emission trend for biodiesel production from rapeseed/canola and soybeans. It is expected that some data will become available in the next year or so as some of the sustainability certification schemes become effective in Europe and elsewhere. Given the age of some of the available data and the information that has been used in various regulatory LCA tools there may be large gaps between the published default values for feedstock production and the actual values.

4. OIL EXTRACTION

Oilseeds are traditionally crushed and solvent extracted in order to separate the oil from the meal. The process usually includes seed cleaning, seed pre-conditioning and flaking, seed cooking, pressing the flake to mechanically remove a portion of the oil, solvent extraction of the press-cake to remove the remainder of the oil, and desolventizing and toasting of the meal.

Some facilities employ only mechanical extraction but the majority of the industry employs the solvent extraction process and the work here only considers the solvent extraction approach.

Some studies of the GHG emissions include a stage of drying the oilseeds prior to oil extraction. This practice is not done in all locations or in all years and the energy requirements for this stage are not included here.

4.1 RAPESEED

While one might expect that the energy consumption for crushing rapeseed is similar no matter where the process is undertaken, there could be some differences related to climate, age of the facilities, and local requirements.

4.1.1 Europe

No single source of industry average data has been identified for European rapeseed crushers. Schmidt (2007) reported the following energy requirements based on data from two companies in Europe. The oil yield was 42%. This is shown below.

Table 4-1 European Rapeseed Mill Energy Requirements

	Per tonne of Rape crushed	Per tonne of Oil produced
Electricity Purchased, kWh	49	116
Natural Gas Purchased, GJ steam	0.67	1.59
Total Energy, GJ	0.84	2.00

The values used in some of the LCA tools are summarized in the following table. Other than the German default value, the results are all quite similar. All of the results appear to be for refined soybean oil. The yields of oil vary from 39 to 42% in these tools.

Table 4-2 LCA Tools - Rapeseed Mill Energy Requirements

	Electricity, kWh/tonne oil	Natural gas, GJ/tonne oil	Total, GJ/tonne oil
JRC	99	1.95	2.30
UK Carbon Tool	94	1.99	2.32
Dutch Carbon Calculator	89	2.02	2.34
Germany default value	95	3.55	3.89

4.1.2 Canada

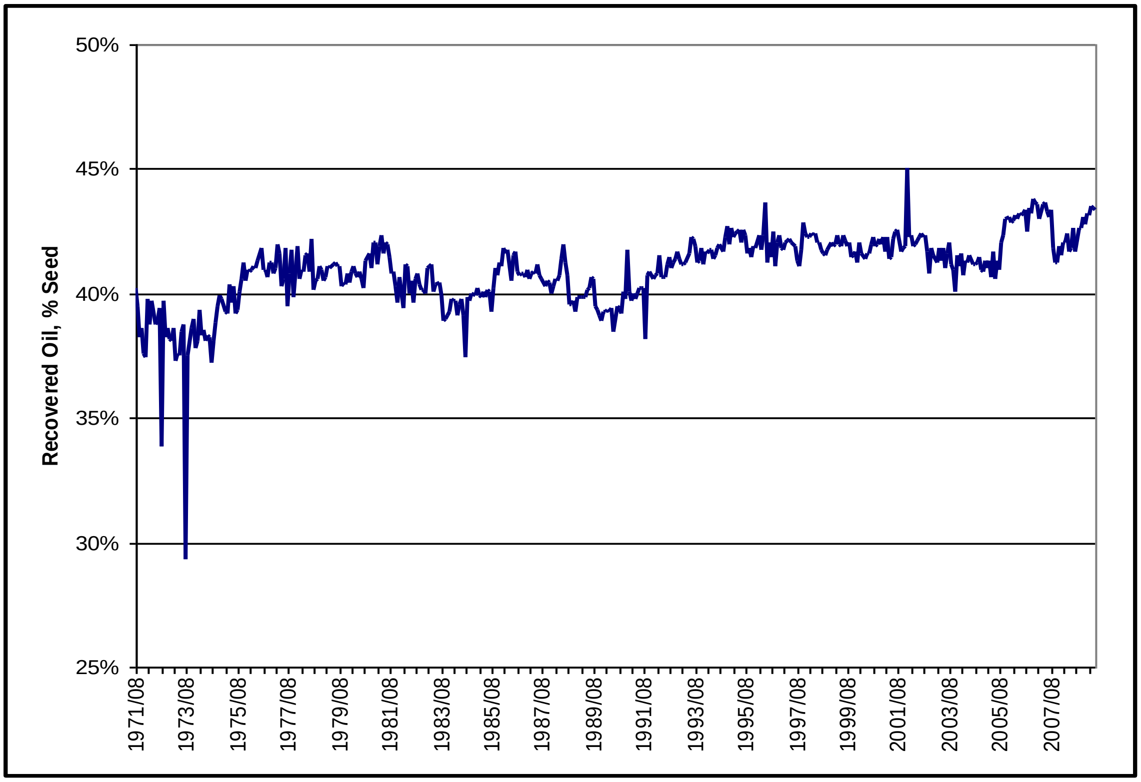
A survey of the canola crushing plants in North America was recently undertaken by Canadian Oilseed Processors Association for the Canola Council in support of the data supplied to the EPA for their RFS2 process. A total of 10 plants in Canada and the United States participated in the survey. All of the plants used natural gas as their source of thermal energy. To the extent possible, the plants normalized their energy requirements to produce the quality of canola oil required for biodiesel production as opposed to the quality used for human food applications. The results from the survey are summarized in the following table. This is the data that is now in GHGenius. The industry energy consumption for Canadian plants is higher than that reported in Europe.

Table 4-3 Canola Crushing Energy Requirements

	Per tonne of Canola crushed	Per tonne of Oil produced
Electricity Purchased, kWh	49	114.5
Natural Gas Purchased, GJ	1.0	2.34
Total Energy, GJ	1.18	2.75

The oil content in the seed is important, but ultimately for a biodiesel LCA, it is the oil that is extracted from the seed that is needed for the analysis. This information is reported monthly by Statistics Canada and is shown in the following figure. This figure has generally increased over time and has averaged 42.8% over the past three years. This oil extraction rate is 2.25 times that of soybeans.

Figure 4-1 Oil Extraction Rates – Canadian Canola Crushers



The specific gravity of the canola oil is 0.914 - 0.917 g/litre. The quantity of seed required to produce a litre of canola oil is therefore 2.15 kg.

4.2 SOYBEANS

The National Oilseed Processors Association published an energy survey of their members in 2009. That data is summarized in the following table. The requirements per tonne of oilseeds crushed is in the same range as rapeseed but when expressed on a per unit of oil produced basis the energy requirements are higher. The soybean oil yield was reported to be 19.5% of the mass of the beans crushed. This is the data that is included in GHGenius.

Table 4-4 Soybean Crushing Energy Requirements (NOPA)

	Per tonne of Soybeans crushed	Per tonne of Oil produced
Electricity Purchased, kWh	55.2	289
Natural Gas Purchased, GJ	1.20	6.29
Total Energy, GJ	1.40	7.33

The values used in some of the LCA tools are summarized in the following table. The results are all quite similar. All of the results appear to be for refined soybean oil. The yields of oil vary from 17-19% in these tools. The results are quite similar and are in line with the reported US industry experience.

Table 4-5 LCA Tools – Soybean Mill Energy Requirements

	Electricity, kWh/tonne oil	Natural gas, GJ/tonne oil	Total, GJ/tonne oil
JRC	351	6.23	7.49
UK Carbon Tool	410	5.45	6.92
Dutch Carbon Calculator	257	6.08	7.00
Germany Default value	338	6.49	7.71

4.3 SUMMARY

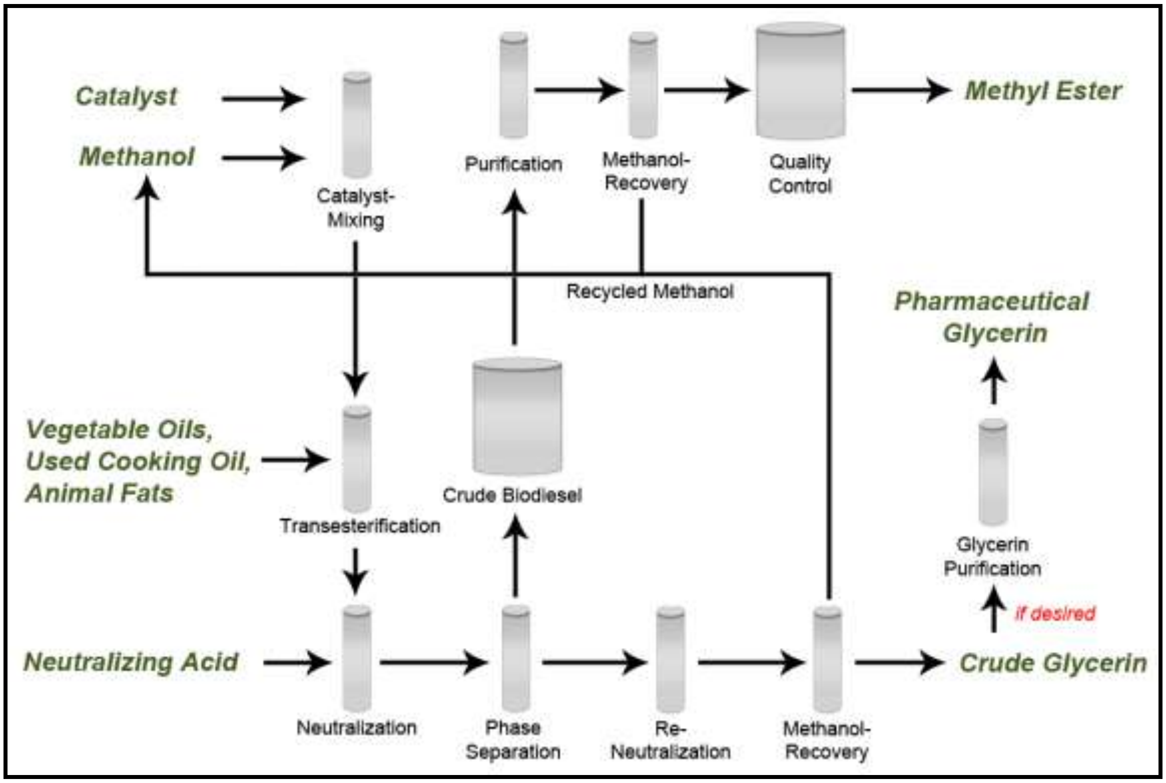
Time series data on the energy requirements for oilseed crushing have not been identified. Only in North America are there industry average values available for the energy requirements for this stage of the lifecycle.

Some of the values that are used in the LCA tools are significantly higher than the data for North America plants and some European plants would suggest is used. Better information for this stage of the lifecycle should become available with the certification of the sustainability of biofuel programs being initiated in Europe.

5. BIODIESEL PRODUCTION

Biodiesel production using rapeseed/canola oil is identical to the production of biodiesel produced from soybean oil. The basic process is shown in the following figure.

Figure 5-1 Biodiesel Production Process



5.1 EUROPE

Berghout (2008) attempted to undertake a survey of the mass and energy balances of the European biodiesel industry but was not successful as most of the companies approached did not wish to release the information.

The values used in the various European LCA tools are summarized in the following table.

Table 5-1 LCA Tools - Biodiesel Energy Requirements

	Electricity, kWh/litre BD	Natural gas, MJ/litre BD	Feedstock, kg/litre BD
JRC	0.026	1.27	0.886
UK Carbon Tool	0.082	1.49	0.925
Dutch Carbon Calculator	0.026	1.33	0.923
Germany Default value	0.040	1.33	0.89

5.2 NORTH AMERICA

In 2009, the National Biodiesel Board (NBB) has conducted the most comprehensive survey of the actual energy used by commercial biodiesel production plants in the world and released the data for public use.

This survey found that for biodiesel produced from virgin vegetable oils, 0.88 kg of oil was used to produce one litre of biodiesel.

The energy consumption data for virgin vegetable oils from the NBB survey is summarized in the following table.

Table 5-2 Biodiesel Energy Use

	Units	NBB
Electricity	kWh/litre	0.032
Natural Gas	L NG/litre biodiesel	20.2
Natural Gas	MJ/litre	0.76

The energy requirements from this survey are lower than typically used in Europe but they represent actually data rather than assumed or unreferenced values.

There are a number of chemicals that are used in the production in addition to the methanol that has been identified above. The NBB survey results for chemical usage are shown in the following table.

Table 5-3 NBB Chemical Inputs

	Units	Value
Methanol	litres/litre biodiesel	0.102
Sodium Methylate	kg/litre biodiesel	0.021
Sodium Hydroxide	kg/litre biodiesel	0.001
Hydrochloric Acid	kg/litre biodiesel	0.039
Phosphoric Acid	kg/litre biodiesel	0.001
Citric Acid	kg/litre biodiesel	0.001

Not all of these chemicals are included in GHGenius. The methylate is proportioned between methanol and sodium hydroxide, sulphuric acid is substituted for citric and hydrochloric acid and phosphate nutrients are substituted for phosphoric acid. The revised inputs are summarized in the following table.

Table 5-4 GHGenius Chemical Inputs

	Units	Value
Methanol	litres/litre biodiesel	0.122
Sodium Hydroxide	kg/litre biodiesel	0.005
Sulphuric Acid	kg/litre biodiesel	0.040
Phosphate nutrients	kg/litre biodiesel	0.001

5.2.1 Co-Products

The biodiesel production process produces crude glycerine and small amounts of fatty acids. The information from the NBB survey is shown in the following table. The fatty acids are treated as a waste in GHGenius.

Table 5-5 NBB Co-product Data

	Value
Glycerine, kg/litre	0.106
Fatty acids, kg/litre	0.002

5.3 SUMMARY

The energy consumed in biodiesel plants has been surveyed in North America but no similar survey for European plants was identified. The energy requirements used in the various LCA tools for biodiesel manufacturing are significantly higher than the average results reported in North America.

No time series of data has been identified for either region.

6. CHANGES IN EMISSIONS WITH TIME

In the previous sections, it has been shown that there have been significant changes in portions of the biodiesel supply chain over time. Most of this change has been in the feedstock production portion of the lifecycle. While an ideal data set (one country, all parameters and a time series) for all aspects of the production systems has not been identified, it is possible to put together the data required to look at and compare the GHG emissions for rapeseed and soybean biodiesel in the years 1995, 2005, and a forward forecast to 2015.

The GHGenius model is used to do this. The model has been set to use the data for Canada with three exceptions, the emission factor for N_2O for fertilizer applied has been set to 1.0% rather than the regional values that the model uses for various regions in Canada, the fraction of nitrogen lost offsite has been set to 0.3 rather than the regional values used for Canada, and the soil carbon change has been set to zero. The 2007 IPCC GWPs are used.

GHGenius has built in trends for most of the parameters in the energy system. Factors such as the carbon intensity of electric power production, the energy intensity of oil production, refining and process emissions from those sources all vary with trends established using historical data and official forecasts. These all remain active except those directly involved in the biodiesel production cycle.

6.1 RAPESEED BIODIESEL

Rapeseed production information from Germany and the UK has been used to develop the three data sets that are used for the modelling since neither country has a complete representative data set. The modelling parameters are summarized in the following table. The data in the table is consistent with the trends that were shown in section 3 of the report.

Table 6-1 Rapeseed Production Parameters

	1995	2005	2015
Yield, t/ha	3.1	3.5	4.05
Fertilizer			
N, kg/ha	170	170	170
P_2O_5, kg/ha	45	42	40
K_2O, kg/ha	13	11.5	10
N, kg/t	54.8	48.6	42.0
P_2O_5, kg/t	14.5	12.0	9.9
K_2O, kg/t	4.2	3.3	2.4
Fuel			
L/ha	65	62.5	60
L/t	21.0	17.9	14.8
Pesticides			
kg a.i/ha	0.30	0.28	0.25
kg a.i./t	0.10	0.08	0.06
Lime			
Kg/ha	20	20	20
Kg/t	6.45	5.71	4.94

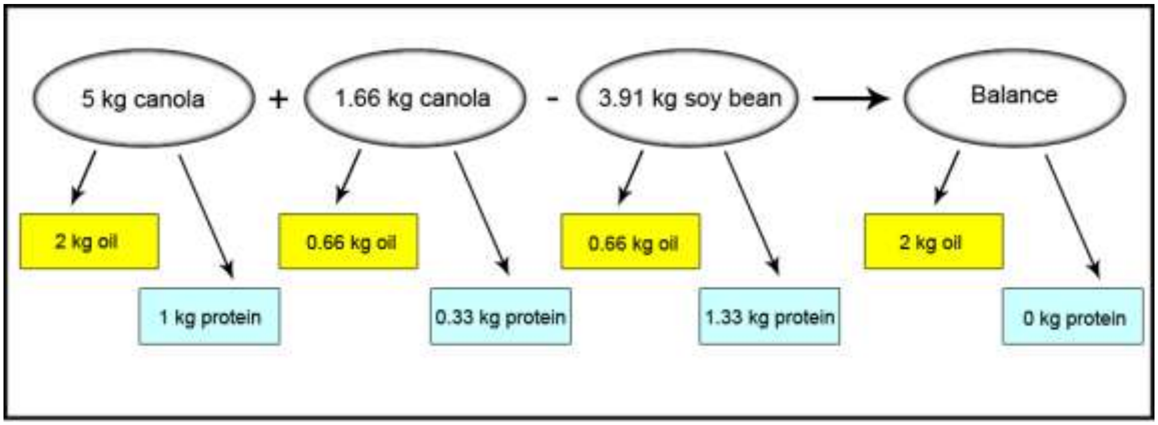
Trend data for oilseed crushing and biodiesel production is not available. For this work it has been assumed to be unchanged. It is also assumed that the oil content of the seed will remain unchanged over this twenty year period. Both assumptions will produce conservative results. The GHG emissions for the three scenarios are shown in the following table and compared to the 1995 diesel fuel emissions.

Table 6-2 Rapeseed Biodiesel GHG Emissions vs. Time

	Diesel Fuel	Rapeseed Biodiesel		
	1995	1995	2005	2015
	g CO_2eq/GJ (HHV)			
Fuel dispensing	131	150	157	122
Fuel distribution and storage	465	1,311	1,219	1,150
Fuel production	5,589	7,634	7,535	7,162
Feedstock transmission	1,015	949	956	980
Feedstock recovery	7,746	5,290	4,540	2,851
Land-use changes, cultivation	130	25,802	21,074	15,785
Fertilizer manufacture	0	11,743	9,743	7,981
Gas leaks and flares	3,221	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-126	-19,032	-20,784	-23,172
Sub-Total	18,170	33,846	24,441	12,860
Combustion Emissions	69,956	1,690	1,740	1,735
Grand Total	88,126	35,536	26,181	14,595
% Reduction		59.6	70.3	83.4

GHGenius uses a system expansion to allocate the emissions between the oil and the meal. The model does this automatically by using the data for soybean and canola production and oil extraction. This makes these two supply chains interdependent. The system expansion is shown in the following figure.

Figure 6-1 Vegetable Oil System Expansion



Relative increases in the emissions for producing soybeans will cause a shift in the allocation of emissions towards the meal and thus we see some shifts in the proportion of emissions allocated to meal in the above table. Even without this shift there is a significant reduction in the emissions associated with growing and crushing rapeseed over time. The pre-allocation emissions are declining at the compound rate of 1.9% per year.

6.2 SOYBEAN BIODIESEL

Soybean production information for the United States is available and there is a reasonably good time series of data with the exception of direct fuel use. The modelling parameters are summarized in the following table. The data in the table is consistent with the trends that were shown in section 3 of the report.

Table 6-3 Soybean Production Parameters

	1995	2005	2015
Yield, t/ha	2.43	2.70	3.01
Fertilizer			
N, kg/ha	4.35	4.83	5.39
P_2O_5, kg/ha	15.45	15.63	15.47
K_2O, kg/ha	27.4	26.0	24.0
N, kg/t	1.79	1.79	1.79
P_2O_5, kg/t	6.36	5.75	5.14
K_2O, kg/t	11.28	9.64	8.00
Fuel			
MJ/ha	2,026	2,020	2,020
MJ/t	834	748	671
Pesticides			
kg a.i/ha	0.30		
kg a.i./t	0.53	0.51	0.50
Lime			
Kg/ha	0	0	0
Kg/t	0	0	0

The GHG emission results are shown in the following table. The rate of decline in the pre-allocation emissions is only 0.3% per year. This is a function of the low nitrogen fertilizer input rates due to the fact that soybeans fix their own nitrogen. N_2O emissions from soybean production are still significant due to the decomposition of the high nitrogen content residues left behind after harvest but little reduction in this component is expected over time.

Table 6-4 Soybean Biodiesel GHG Emissions vs. Time

	Diesel Fuel	Soybean Biodiesel		
	1995	1995	2005	2015
	g CO_2eq/GJ (HHV)			
Fuel dispensing	131	150	157	122
Fuel distribution and storage	465	950	922	905
Fuel production	5,589	14,821	14,635	13,885
Feedstock transmission	1,015	1,917	1,932	1,979
Feedstock recovery	7,746	10,915	9,614	8,846
Land-use changes, cultivation	130	32,485	32,419	32,392
Fertilizer manufacture	0	6,615	6,055	5,665
Gas leaks and flares	3,221	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-126	-27,180	-34,492	-39,342
Sub-Total	18,170	40,673	31,243	24,452
Combustion Emissions	69,956	1,690	1,740	1,735
Grand Total	88,126	42,363	32,983	26,187
% Reduction		51.9	62.6	70.3

6.3 OPPORTUNITY FOR PERFORMANCE IMPROVEMENT

The results presented above show that the GHG emission performance of rapeseed and soybean biodiesel has improved over time and that further improvements can be expected in the future. Most of this improvement is a result of increased yields with constant or reducing fertilizer applications. There are other innovations, such as no till agriculture, that either have been adopted in some parts of the world or are in the process of adoption that are not included in the previous calculations. There could also be improvements in processing the oilseeds and oils that could be introduced and the impact of these is considered in the following sections.

6.3.1 Agricultural Practices

There are two agricultural practices that can have a significant impact on the GHG emissions from crop production, the implementation of no till cultivation and the adoption of sloe release nitrogen fertilizers. While both of these practices are employed in parts of the world today, their impact is not fully included in the calculations shown above.

6.3.1.1 No Till

No-till farming (sometimes called zero tillage) is a way of growing crops from year to year without disturbing the soil through tillage. No-till is an emergent agricultural technique, which can increase the amount of water in the soil and decrease erosion. Tilling is used to remove weeds, mix in soil amendments like fertilizers, shape the soil into rows for crop plants and furrows for irrigation, and prepare the surface for seeding. This can lead to unfavourable effects, like soil compaction; loss of organic matter; degradation of soil aggregates. No-till farming avoids these effects by excluding the use of tillage. With this way of farming, crop residues or other organic amenities are retained on the soil surface and sowing/fertilizing is done with minimal soil disturbance.

Less tillage of the soil reduces labour, fuel, in some cases irrigation and machinery costs. No-till has carbon sequestration potential through storage of soil organic matter in the soil of crop fields. Tilled by machinery, the soil layers invert, air mixes in, and soil microbial activity dramatically increases over baseline levels. The result is that soil organic matter is broken down much more rapidly, and carbon is lost from the soil into the atmosphere.

The impact of reduced fuel consumption and increases in soil carbon are discussed below.

6.3.1.1.1 Fuel Consumption

Of all of the mechanical operations involved in crop production, tillage is the most energy intensive as the soil must be mechanically broken and inverted with a plow. This primary tillage can consumed more than 15 litres/ha of diesel fuel alone (Downs et al, 1998). The USDA has a fuel consumption calculator on the internet (http://ecat.sc.egov.usda.gov/). Users can enter their zip code and the calculator will compute the fuel used per acre to grow various crops using different tillage methods. The results for a North Dakota location (Minot) are shown in the following table. North Dakota produces most of the US canola crop. The range of fuel consumption between full tillage and no till is greater than the Canadian estimates and more in line with other estimates, but the values for conventional tillage are in the same range.

Table 6-5 North Dakota Fuel Consumption Factors

	Conventional tillage	Mulch Tillage	No Till	No Till Savings
	Litres Diesel/ha			
Canola	-	35.9	17.3	18.6
Soybeans	-	35.9	17.3	18.6
Wheat	35.9	34.8	17.3	17.6

The impact of reducing the fuel consumption for rapeseed and soybeans by 18 litres diesel/ha on the 2005 GHG emissions shown earlier are shown in the following table.

Table 6-6 Impact of Reduced Fuel Use on Biodiesel GHG Emissions

Feedstock	Rapeseed		Soybeans	
Year	2005			
Scenario	Current Fuel	Reduced Fuel	Current Fuel	Reduced Fuel
	g CO_2eq/GJ (HHV)			
Fuel dispensing	157	157	157	157
Fuel distribution and storage	1,219	1,219	922	922
Fuel production	7,535	7,535	14,635	14,635
Feedstock transmission	956	956	1,932	1,932
Feedstock recovery	4,540	3,234	9,614	6,280
Land-use changes, cultivation	21,074	21,074	32,419	32,419
Fertilizer manufacture	9,743	9,743	6,055	6,055
Gas leaks and flares	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-20,784	-20,145	-34,492	-31,824
Total	24,441	23,774	31,243	30,576
% Reduction		2.7		2.1
% Reduction before co-product allocation		2.9		5.1

A fuel use reduction of 18 l/ha is a relatively conservative scenario. Fuel use per hectare for canola in Canada is already below the reduced value use for modelling, nevertheless this does produce a 3-5% reduction in the lifecycle GHG emissions for rapeseed and soybean biodiesel.

6.3.1.1.2 Soil Carbon Changes

One of the major benefits of the no till production method is that soil carbon usually increases with continual use of no till practices. The impact of an increase in soil carbon of 0.3 t CO_2eq/ha is shown in the following table for rapeseed and soybeans.

Table 6-7 Impact of Soil Carbon Changes on Biodiesel GHG Emissions

Feedstock	Rapeseed		Soybeans	
Year	2005			
Scenario	No Soil Carbon Change	Increased Soil Carbon	No Soil Carbon Change	Increased Soil Carbon
	g CO_2eq/GJ (HHV)			
Fuel dispensing	157	157	157	157
Fuel distribution and storage	1,219	1,219	922	922
Fuel production	7,535	7,535	14,635	14,635
Feedstock transmission	956	956	1,932	1,932
Feedstock recovery	4,540	4,540	9,614	9,614
Land-use changes, cultivation	21,074	15,866	32,419	17,402
Fertilizer manufacture	9,743	9,743	6,055	6,055
Gas leaks and flares	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-20,784	-17,693	-34,492	-21,591
Total	24,441	22,325	31,243	29,127
% Reduction		8.7		6.8
% Reduction before co-product allocation		11.5		22.8

The reductions are quite significant (12 to 28%). The lower yield of soybeans produces a larger reduction on a per unit of biodiesel basis and it also allocates more of the emissions to the oil.

6.3.1.1.3 Controlled Release Nitrogen Fertilizer

Controlled release fertilizers are being utilized in North America. These fertilizers are coated with a polymeric coating that controls the release of a nitrogen solution according to soil temperature. This results in two benefits, the nitrogen utilization efficiency is improved, and the N_2O emissions are reduced. Better nitrogen utilization will result in either lower nitrogen application rates or higher yields. Since the yield response rate for most crops is non-linear the impact of lower fertilization rates (up to 20% lower in tests) will be larger than the impact of higher yields (5 to 7% higher for corn).

The impact on N_2O emission rates depends on when the fertilizer is applied. Reductions of 20 to 50% have been seen in field trials in Canada. The impact of a 20% reduction in the N_2O emission factor for synthetic fertilizer only (not for the emissions from residue decomposition) is shown in the following table. No allowance for improved yield or reduced fertilizer application is assumed.

Table 6-8 Impact of Controlled Release Fertilizer on Biodiesel GHG Emissions

Feedstock	Rapeseed		Soybeans	
Year	2005			
Scenario	Base	Controlled Release fertilizer	Base	Controlled Release fertilizer
	g CO_2eq/GJ (HHV)			
Fuel dispensing	157	157	157	157
Fuel distribution and storage	1,219	1,219	922	922
Fuel production	7,535	7,535	14,635	14,635
Feedstock transmission	956	956	1,932	1,932
Feedstock recovery	4,540	4,540	9,614	9,614
Land-use changes, cultivation	21,074	18,623	32,419	32,156
Fertilizer manufacture	9,743	9,743	6,055	6,055
Gas leaks and flares	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-20,784	-21,474	-34,492	-37,369
Total	24,441	21,300	31,243	28,103
% Reduction		12.9		10.1
% Reduction before co-product allocation		5.4		0.4

The reductions on rapeseed are larger since the quantity of nitrogen fertilizer applied to soybeans is very small. Making changes in one system without the same change in the other system does change the allocation results in GHGenius. In this case, more of the emissions are transferred to the meal and the % reductions for biodiesel are larger than they are for just the crop production.

6.3.2 Processing Improvements

While there is no data available on the rate of change of energy use in the oilseed crushing and esterification industries, it is possible to model the impact of a 10% reduction in energy use on the lifecycle GHG emissions.

6.3.2.1 Oil Extraction

The energy used in oil extraction is mostly thermal energy (assumed produced from natural gas) and electricity. The combined impact of a 10% reduction in gas and power use is shown in the following table.

Table 6-9 Impact of Lower Oilseed Crushing Energy on Biodiesel GHG Emissions

Feedstock	Rapeseed		Soybeans	
Year	2005			
Scenario	Base	10% reduction in energy use	Base	10% reduction in energy use
	g CO_2eq/GJ (HHV)			
Fuel dispensing	157	157	157	157
Fuel distribution and storage	1,219	1,219	922	922
Fuel production	7,535	7,125	14,635	13,554
Feedstock transmission	956	956	1,932	1,932
Feedstock recovery	4,540	4,540	9,614	9,614
Land-use changes, cultivation	21,074	21,074	32,419	32,419
Fertilizer manufacture	9,743	9,743	6,055	6,055
Gas leaks and flares	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-20,784	-20,784	-34,492	-34,492
Total	24,441	24,030	31,243	30,162
% Reduction		1.7		3.5
% Reduction before co-product allocation		0.9		1.6

The reductions in the lifecycle GHG emissions are quite small from a 10% reduction in crushing energy use, reflecting the small contribution that these emissions have on the overall lifecycle.

6.3.2.2 Oil Content

Plant breeders have been working on varieties that have higher oil contents. They have had some success with rapeseed but less success with soybeans. The impact of 10% higher oil contents in both crops is shown in the following table.

Table 6-10 Impact of High Oil Contents on Biodiesel GHG Emissions

Feedstock	Rapeseed		Soybeans	
Year	2005			
Scenario	Base	10% increase in oil content	Base	10% increase in oil content
	g CO_2eq/GJ (HHV)			
Fuel dispensing	157	157	157	157
Fuel distribution and storage	1,219	1,219	922	922
Fuel production	7,535	7,535	14,635	14,635
Feedstock transmission	956	884	1,932	1,771
Feedstock recovery	4,540	4,128	9,614	8,741
Land-use changes, cultivation	21,074	19,162	32,419	29,475
Fertilizer manufacture	9,743	8,860	6,055	5,506
Gas leaks and flares	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-20,784	-20,129	-34,492	-32,588
Total	24,441	21,817	31,243	28,619
% Reduction		10.7		8.4
% Reduction before co-product allocation		7.7		6.9

Increased oil content reduces the emissions through most of the supply chain. Making the same percentage change to rapeseed and canola shifts some of the emissions back to the oil in the GHGenius system expansion. The reduction in emissions is still significant.

6.3.2.3 Esterification

Another area of potential improvement in energy use is in the biodiesel production process itself. The impact of a 10% reduction in energy use (power and gas) is shown in the following table. The impact is very small, again showing the low impact of the biodiesel production process on the overall lifecycle emissions for vegetable oil biodiesel.

Table 6-11 Impact of Lower Biodiesel Processing Energy on Biodiesel GHG Emissions

Feedstock	Rapeseed		Soybeans	
Year	2005			
Scenario	Base	10% reduction in energy use	Base	10% reduction in energy use
	g CO_2eq/GJ (HHV)			
Fuel dispensing	157	157	157	157
Fuel distribution and storage	1,219	1,219	922	922
Fuel production	7,535	7,377	14,635	14,476
Feedstock transmission	956	956	1,932	1,932
Feedstock recovery	4,540	4,540	9,614	9,614
Land-use changes, cultivation	21,074	21,074	32,419	32,419
Fertilizer manufacture	9,743	9,743	6,055	6,055
Gas leaks and flares	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-20,784	-20,784	-34,492	-34,492
Total	24,441	24,282	31,243	31,085
% Reduction		0.7		0.5
% Reduction before co-product allocation		0.4		0.2

6.3.3 Summary

The available data on the supply chain for rapeseed and soybean biodiesel would indicate that the GHG emissions for these vegetable oil biodiesel fuels have decreased from 1995 to 2005, and if the present trends continue there should be further reductions in the emissions in the future. The emissions for rapeseed biodiesel have been declining at 1.9% per year and for soybean biodiesel at 0.6% per year. These rates may be conservative because the quality of the data for some parts of the supply chain has been poor.

A number of areas for improvement in the GHG emissions have been identified and the emissions impact of each has been estimated. All of the improvements identified are currently being practiced in some parts of the world but not by all participants in the supply chain. The greatest area for improvement is in the feedstock production. The potential GHG improvements in oilseed crushing and biodiesel production are relatively small.

The cumulative impact of all of the changes identified is shown in the following table. These include no till management practices that reduce fuel use, increase soil carbon, the use of controlled release nitrogen fertilizer to reduce N_2O emissions, increased oil content of the seeds and lower energy consumption in the oilseed crushers and biodiesel processors.

Table 6-12 Cumulative Impact of All Improvements on Biodiesel GHG Emissions

Feedstock	Rapeseed		Soybeans	
Year	2005			
Scenario	Base	Cumulative Impact	Base	Cumulative Impact
	g CO_2eq/GJ (HHV)			
Fuel dispensing	157	157	157	157
Fuel distribution and storage	1,219	1,219	922	922
Fuel production	7,535	6,967	14,635	13,354
Feedstock transmission	956	881	1,932	1,769
Feedstock recovery	4,540	2,577	9,614	2,494
Land-use changes, cultivation	21,074	12,136	32,419	15,565
Fertilizer manufacture	9,743	8,814	6,055	5,499
Gas leaks and flares	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-20,784	-16,732	-34,492	-17,651
Total	24,441	16,019	31,243	22,109
% Reduction		34.5		29.2
% Reduction before co-product allocation		27.6		39.5

The cumulative change in GHG emissions is greater than that forecast for 2015 based in the continuation of the existing trends when considered on a pre-allocation basis. The impact of all of the changes on the system expansion allocation process in GHGenius allocates more of the emission reductions to the meal and thus the oil carries a lager proportion of the emissions burden in the low emission scenario.

7. REGIONAL DIFFERENCES IN GHG EMISSIONS

In section 3 of the report it was shown that agricultural practices vary from region to region. One would therefore expect that the GHG emissions for biodiesel made from these crops would also vary. This issue is investigated in this section.

7.1 RAPESEED

The GHG emissions for rapeseed biodiesel are strongly influenced by agricultural practices and the emissions arising from those practices. Two aspects are investigated here, the first is the impact of the farming practices between countries, and the second involves issues out of the direct control of producers such as the emissions from fertilizer production and application.

7.1.1 Agricultural Practices

Information on the production of rapeseed or canola for Canada, the UK, and Germany was presented in section 3. The data sets for each country were not complete but the data gaps can be filled in or assumed. The primary data used for this modelling is shown in the following table. The data is for the year 2005. Yield data represents average yield for 2004-2006 to reduce the year to year variation.

Table 7-1 Regional Production Data

		Canada	UK	Germany
Yields	tonne/ha	1.49	3.13	3.87
N	kg/tonne	48.8	63.3	48.3
P_2O_5	kg/tonne	16.6	12.1	12.8
K_2O	kg/tonne	3.9	13.4	5.0
Lime	kg/tonne	0	3.3	5.7
Pesticide	kg a.i./tonne	0.80	0.08	0.08
S	kg/tonne	7.8	11.8	0
Fuel	litres/tonne	30	21	17

For the modelling, all of the other parameters are held constant, so the same emission intensity is used for fossil fuels and for electric power. This allows the isolation of the factors under the influence of the agricultural producer. The results are shown in the following table.

Table 7-2 Rapeseed Biodiesel Regional Differences

	Canada	UK	Germany
	g CO_2eq/GJ (HHV)		
Fuel dispensing	157	157	157
Fuel distribution and storage	1,219	1,219	1,219
Fuel production	7,535	7,535	7,535
Feedstock transmission	956	956	956
Feedstock recovery	7,609	5,326	4,312
Land-use changes, cultivation	20,985	26,083	20,960
Fertilizer manufacture	10,883	12,643	9,767
Gas leaks and flares	0	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-19,486	-18,044	-20,885
Total	29,860	35,876	24,022

The UK emissions are higher, primarily as a result of the higher nitrogen fertilizer application rates. The German results are the lowest and benefit from the highest yield, which reduces the feedstock fuel related emissions. The difference in the results between Germany and the UK are significant as the higher nitrogen application rates increase the GHG emissions by 20%.

7.1.2 Fertilizer Production and Use

There can also be regional differences in emissions that are mostly out of the control of feedstock producer. For rapeseed, two of the most significant are the manufacturing emissions of the nitrogen fertilizer and the N_2O emission rate from the applied nitrogen fertilizer. Both are discussed below.

7.1.2.1 Emissions from Nitrogen Fertilizer Manufacturing

Patyk (1996), Brentrup (2008), and Kongshaug (2003) have all presented estimates of the GHG emissions for different types of nitrogen fertilizers. Their results are shown in the following table. It is apparent from the table that the type of fertilizer that is applied can have a large impact on the emissions that are embodied in the material.

Table 7-3 GHG Emissions Nitrogen Fertilizer

	Patyk	Konsghaug	Brentrup
		World Average	2006 European average
	kg CO_2eq/kg N		
Urea[3]	2.74	3.33	3.17
Urea ammonium nitrate[3]	5.39	5.67	5.93
Calcium ammonium nitrate	8.17	-	6.34
Ammonium Nitrate	-	7.11	6.20
Ammonia	2.35	2.70	-

---

[3] Adjusted to account for CO_2 released in the soil.

There are large differences in the types of nitrogen fertilizer applied in the different regions. The types of nitrogen fertilizer use in Canada (CFI, 2009), the UK (DEFRA, 2010b), and Western Europe (EFMA, 2010) are summarized in the following table.

Table 7-4 Types of Nitrogen Fertilizer Applied

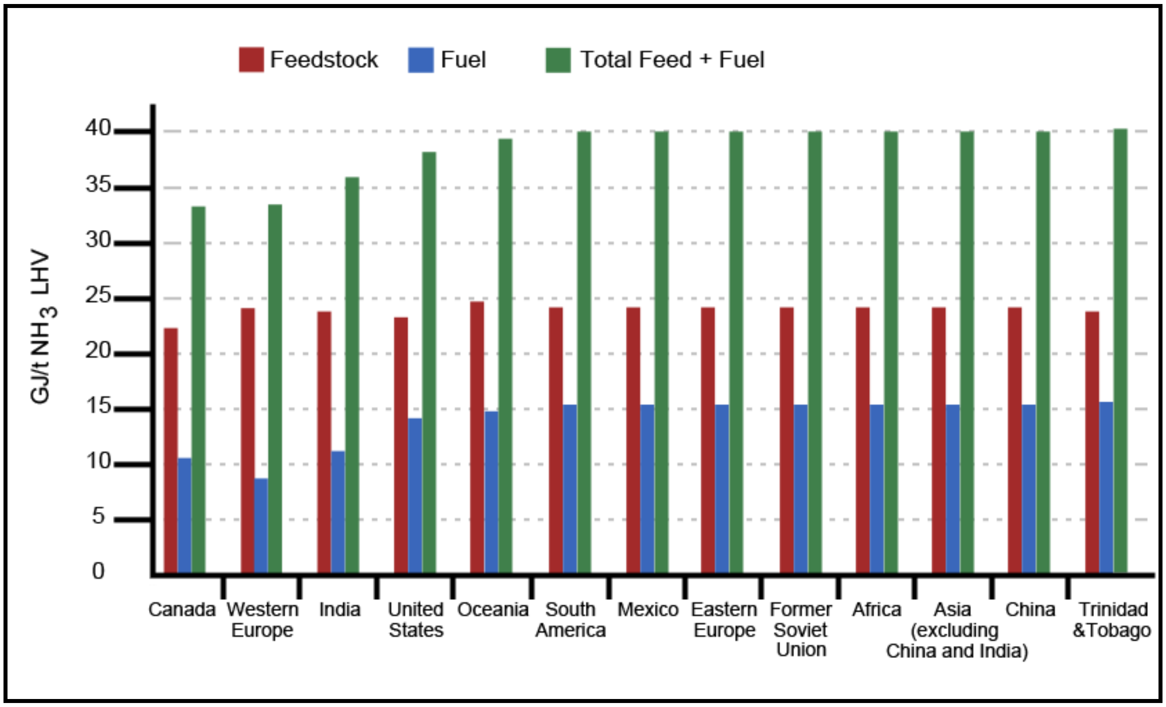
	Canada	UK	Western Europe
Urea	54.3	13.7	18
Urea ammonium nitrate	10.6	6.2	12
Calcium ammonium nitrate	0.0	1.5	24
Ammonium Nitrate	0.0	51.8	19
Ammonia	27.9	0.0	0
Other	7.2	26.8	27

Using the average values from Table 7-3 (with “other” being the average of the four types of fertilizer) and the fraction of each fertilizer applied then the emission factor for nitrogen fertilizer production would be 3.34 kg CO_2eq/kg of N for Canada, 5.68 for the UK and 5.60 for western Europe.

There is the possibility that most of the emission factors in Table 7-3 are too high as they are from older sources and don’t represent the technological advances that have been made in the industry over the past decade. A recent report in the Netherlands (NL Agency, 2010) reported that the GHG emissions for one manufacturer were 2.34 kg CO_2/kg N, although the system boundaries and the type of fertilizer produced were not specified.

It is also known that there are regional differences in technology and efficiency, which are reflected in the values shown here. The following figure is from an NRCan report (2007) that benchmarked the energy efficiency performance of the Canadian ammonia industry. There would be a similar trend in GHG emissions.

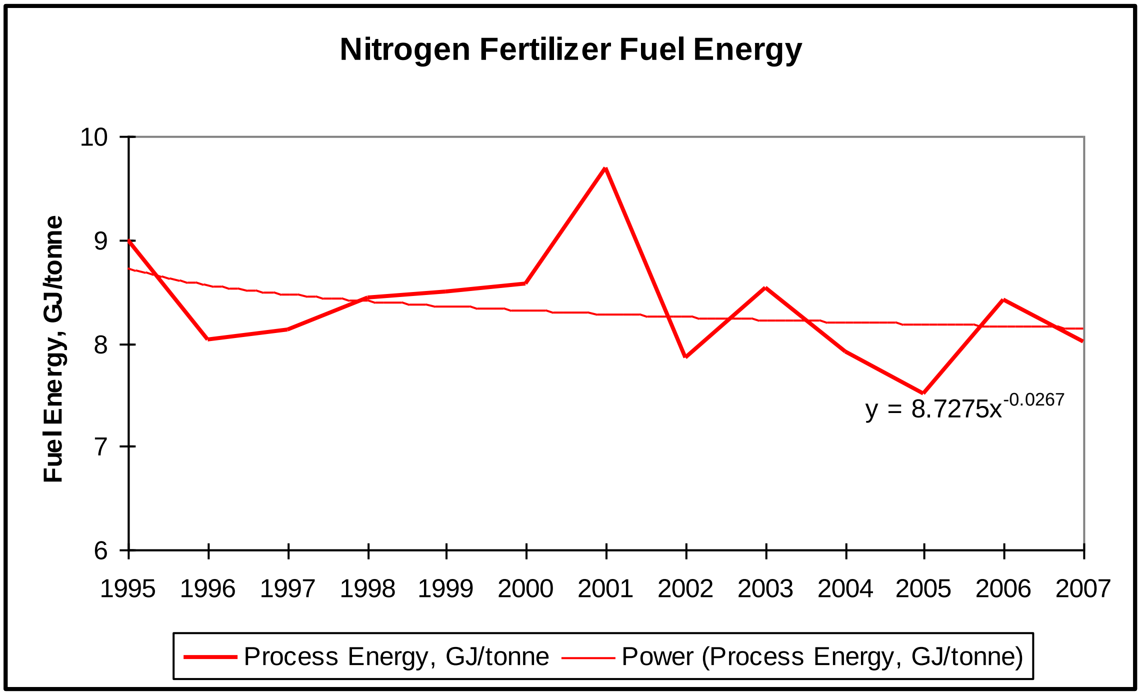
Figure 7-1 Regional Ammonia Plant Energy Efficiency



The default value in GHGenius for the nitrogen fertilizer production emissions is 2.87 kg CO_2eq/kg N, reflecting the efficient nature of the Canadian industry and the low quantities of nitrate fertilizers produced in Canada.

It is highly likely that the nitrogen fertilizer industry shows some trends towards improved energy efficiency. The following data set shows the fuel energy use trend in the Canadian nitrogen fertilizer industry and it can be seen that there is a small downward trend in energy use. This covers only the fuel energy and not the feedstock energy so it does not indicate the total GHG emissions.

Figure 7-2 Trends in Fuel Energy Use Canadian Nitrogen Fertilizer Sector



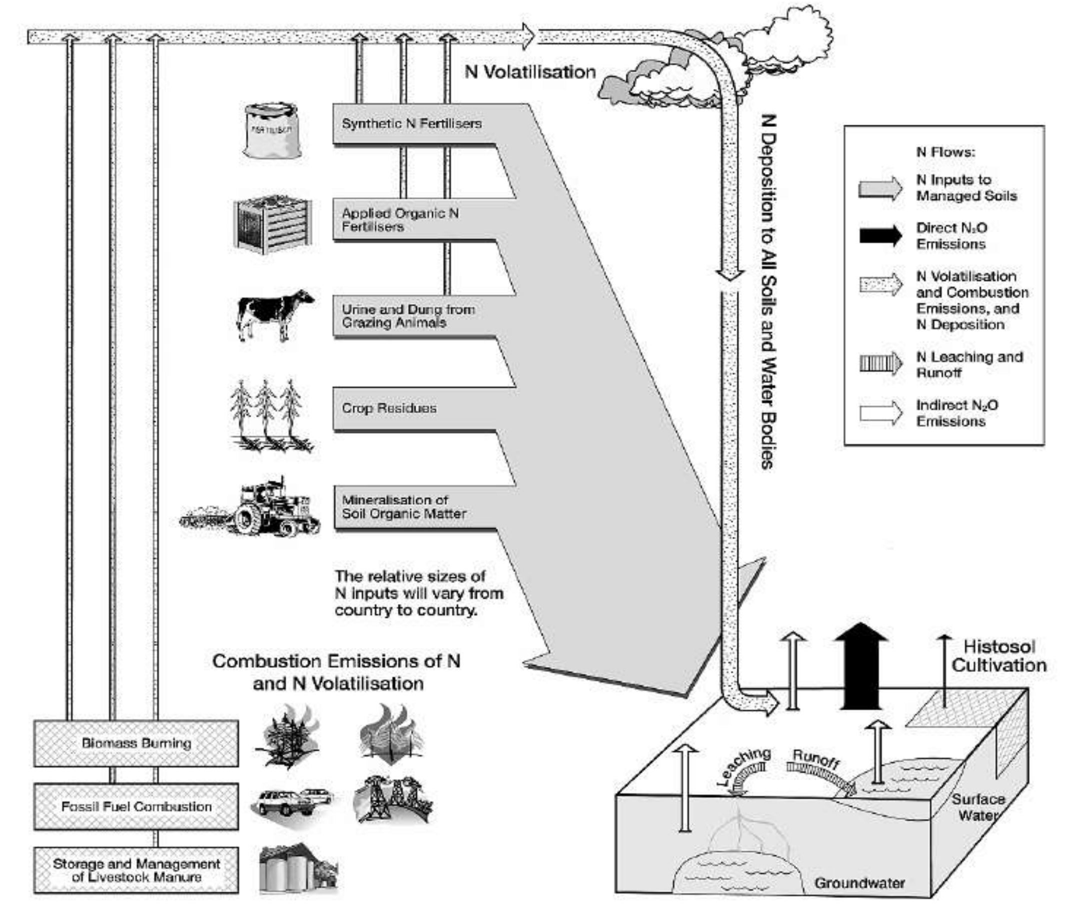
7.1.2.2 Emissions from Nitrogen Fertilizer Application

The application of nitrogen fertilizers also creates N_2O emissions. The rate of N_2O emitted is a function of soil type, moisture levels, temperature and other factors. All of these factors will vary from region to region.

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) have been built upon a body of work that has evolved since the first Guidelines were published in 1996 (IPCC, 1996). These new guidelines include new sources and gases as well as updates to the previously published methods whenever scientific and technical knowledge have improved since the previous guidelines were issued. The GHGenius model follows the latest methodology recommended by the IPCC and allows for a thorough analysis of the N_2O emissions from crop production.

The sources of N_2O emissions covered by the IPCC are shown in the following figure. Most of the sources are an important part of the biofuel production pathways with the exception of animal manure and dung.

Figure 7-3 N_2O Emissions



For biofuel systems the most important parameters from a regional perspective are the application rate and emission factor (EF_1) for synthetic nitrogen fertilizer, the nitrogen content of the crop residues, and the leaching rates and run-off emission factor (EF_5)

The 2006 IPCC Guidelines generally provide advice on estimation methods at three levels of detail, from Tier 1 (the default method) to Tier 3 (the most detailed method). The advice consists of mathematical specification of the methods, information on emission factors or other parameters to use in generating the estimates, and sources of activity data to estimate the overall level of net emissions (emission by sources minus removals by sinks).

Properly implemented, all tiers are intended to provide unbiased estimates, and accuracy and precision should, in general, improve from Tier 1 to Tier 3. The provision of different tiers enables inventory compilers to use methods consistent with their resources and to focus their efforts on those categories of emissions and removals that contribute most significantly to national emission totals and trends.

For the three regions being compared here, the emission factors and Tier employed in each country's National Inventory Reports (Environment Canada, 2010, German Federal Environment Agency, 2010, AEA Technology plc., 2010) are summarized in the following table.

Table 7-5 Summary Of Emission Factors

	Canada[4]	UK	Germany
Approach	Tier 2	Tier 1	Tier 1
EF_1	0.0076	0.0125	0.0125
Fraction leached	0.05	0.30	0.30
EF_5	0.0075	0.025	0.0075

The UK and German values for EF_1 are from the 1996 guidelines and the new value for this factor from the 2005 guidelines is 0.010, however with the moisture that is available for this crop in these countries it is likely that the actual emission factor is above the default value. Both countries are still using the 0.0125 value in their 2008 National Inventory reports.

The EF_5 value use by Germany is the default value from the 2006 guidelines and the UK value is at the upper end of the range for this parameter in the 2006 guidelines but it was the default value in the 1996 guidelines.

The Canadian values represent the semi arid production region of western Canada that produces the majority of the canola in Canada. These values are significantly different from the Tier values use in the UK and German inventory reports. Both the UK and Germany employ the Tier 1 approach so it is possible that the actual emission factors are different from the default values employed.

7.1.2.3 Impact of Regional Factors

Since GHGenius uses the IPCC methodology for calculating the N_2O emissions for biomass production it is a relatively simple matter to use the regional factors used by the national governments in the model to determine the impact on the emissions. For each country, two scenarios are shown, in the first only the emissions from nitrogen fertilizer are changed and in the second the revised manufacturing emissions are combined with the emission factors used in each countries national report. The first table presents the results for Canada.

Table 7-6 Canada – Impact of Regional Factors

	Canada		
	Base	Adj N Fert Production Emissions	Adj N_2O Emission Factors
	g CO_2eq/GJ (HHV)		
Fuel dispensing	157	157	157
Fuel distribution and storage	1,219	1,219	1,219
Fuel production	7,535	7,535	7,535
Feedstock transmission	956	956	956
Feedstock recovery	7,609	7,609	7,609
Land-use changes, cultivation	20,985	20,985	13,985
Fertilizer manufacture	10,883	12,909	12,909
Gas leaks and flares	0	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-19,486	-22,796	-25,002
Total	29,860	28,575	19,369

---

[4] Values for region where canola is produced.

Applying the fertilizer production emission factors for the European industry increases the GHG emissions for Canadian canola biodiesel but combining these emission factors with the Canadian factors for the N_2O emissions from the application of fertilizer reduces the emissions, both in absolute terms and through the allocation of more of the emissions to the protein meal.

The results for the UK are shown in the following table.

Table 7-7 UK – Impact of Regional Factors

	UK		
	Base	Adj Fert Production Emissions	Adj N_2O Emission Factors
	g CO_2eq/GJ (HHV)		
Fuel dispensing	157	157	157
Fuel distribution and storage	1,219	1,219	1,219
Fuel production	7,535	7,535	7,535
Feedstock transmission	956	956	956
Feedstock recovery	5,326	5,326	5,326
Land-use changes, cultivation	26,083	26,083	42,334
Fertilizer manufacture	12,643	24,468	24,468
Gas leaks and flares	0	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-18,044	-14,547	-9,425
Total	35,876	51,198	72,571

The high proportion of ammonium nitrate fertilizer used in the UK results in high emissions for fertilizer production, almost twice the default value in GHGenius for Canada. The higher emission factor for N_2O emissions combined with the high nitrogen fertilizer rate increases the emissions even further. 15,000 g CO_2eq /GJ are due to the use of the old 0.025 emission factor for EF_5 rather than the more recent default value of 0.0075.

The results for Germany are shown in the following figure.

Table 7-8 Germany – Impact of Regional Factors

	Germany		
	Base	Adj Fert Production Emissions	Adj N_2O Emission Factors
	g CO_2eq/GJ (HHV)		
Fuel dispensing	157	157	157
Fuel distribution and storage	1,219	1,219	1,219
Fuel production	7,535	7,535	7,535
Feedstock transmission	956	956	956
Feedstock recovery	4,312	4,312	4,312
Land-use changes, cultivation	20,960	20,960	24,770
Fertilizer manufacture	9,767	18,539	18,539
Gas leaks and flares	0	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-20,885	-20,417	-19,216
Total	24,022	33,262	38,273

The results for Germany reflect the higher emissions for nitrogen fertilizer manufacturing and the higher N_2O emissions from fertilizer application but are lower than the results for the UK due to the lower nitrogen fertilizer application rate in Germany.

The following table compares the adjusted emissions for the three countries. Compared to Table 7-2, which compared the differences resulting from agricultural practices, these differences are much larger and the relative order is different. Germany had the lowest emissions when just the agricultural practices were varied but when the regional fertilizer manufacturing emissions and the regional N_2O emission factors are included, the emissions for Canada are by far the lowest.

Table 7-9 Comparison with Regional Factors

	Canada	UK	Germany
	g CO_2eq/GJ (HHV)		
Fuel dispensing	157	157	157
Fuel distribution and storage	1,219	1,219	1,219
Fuel production	7,535	7,535	7,535
Feedstock transmission	956	956	956
Feedstock recovery	7,609	5,326	4,312
Land-use changes, cultivation	13,985	42,334	24,770
Fertilizer manufacture	12,909	24,468	18,539
Gas leaks and flares	0	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-25,002	-9,425	-19,216
Total	19,369	72,571	38,273

7.2 OTHER REGIONAL DIFFERENCES

Other differences have been identified in potassium and phosphorus fertilizers and other chemical inputs that could reflect either regional differences, data from different time periods, or methodological issues. It has not been possible to identify which driver is primarily responsible for the differences in this project but the differences are presented here to identify the issues.

Potassium fertilizer is used in all crop production systems, the GHG emissions for this fertilizer, used in the various lifecycle tools investigated in this work are shown in the following table. These values are relatively close.

Table 7-10 GHG Emissions Potassium Fertilizer

Source	Value, g CO_2eq/kg	Comments
GHGenius	377	Canadian production, annual energy use surveys
GREET	638	US production
RFA Calculator	333	Kongshaug
SenterNovem Calculator	453	Mortimer
JRC/BioGrace	580	Kaltschmitt & Reinhardt, 1997

Phosphorus fertilizer is also used in all crop production systems; the GHG emissions for this fertilizer used in the various lifecycle tools investigated in this work are shown in the following table. These values are relatively close. There is a wider range in these values than there is in the potassium values.

Table 7-11 GHG Emissions Phosphorus Fertilizer

Source	Value, g CO_2eq/kg	Comments
GHGenius	753	Estimate
GREET	1,008	US Production
RFA Calculator	354	Kongshaug
SenterNovem Calculator	700	Mortimer
JRC/BioGrace	1,014	Kaltschmitt & Reinhardt, 1997

There is relatively little published on the emissions intensity of pesticides. Most tools rely on estimates that were developed in the 1970 and 1980s. Some of the producers are know to be working on documenting their actual performance. Monsanto (2009) have stated that they have reduced the GHG emissions by 24% between 2000 and 2007. Estimates based on information from the 1980's are likely to be different than current performance.

Table 7-12 GHG Emissions Pesticides

Source	Value, kg CO_2eq/kg	Comments
GHGenius	22.2	Based on 1980's estimate
GREET	21.1	Based on 1980's estimate
RFA Calculator	17.3	Kongshaug
SenterNovem Calculator	16.6	Mortimer
JRC/BioGrace	11.0	Kaltschmitt & Reinhardt, 1997

The GHG emissions for the production and oxidation of methanol in the various tools are shown in the following table. Some of the values are very high.

Table 7-13 GHG Emissions Methanol

Source	Value, kg CO_2eq/MJ	Comments
GHGenius	89.9	
GREET	97.5	
RFA Calculator	138.0	Mortimer (Kaltschmitt & Reinhardt, 1997)
SenterNovem Calculator	138.0	Mortimer (Kaltschmitt & Reinhardt, 1997)
JRC/BioGrace	100.5	Haldor Topsoe, 1998

7.3 SUMMARY

This section examined the differences in GHG emissions for the same biofuel pathway practiced in different regions. The agricultural practices and GHG emission results for essentially the same crop are somewhat different in Canada, the UK and Germany. Germany benefits from high yield and good nitrogen fertilizer utilization and as a result the biodiesel produced there has the lowest GHG emissions when all other factors are held constant.

Much larger differences in GHG emissions have been identified from regional factors that are generally beyond the control of the feedstock producer. The production of nitrogen fertilizer is quite different from region to region, with different products being produced and different technologies being employed. European regions appear to use more nitrate-based fertilizers (ammonium nitrate, calcium nitrate, etc.) whereas in North America the ammonium-based fertilizers are more prevalent (ammonia and urea). There are large differences in the GHG emissions associated with the different types of fertilizers and this has a significant impact on the biodiesel lifecycle emissions.

While it is possible for individual feedstock producers to decide to switch types of fertilizer used and reduce the emissions associated with their production, the ability to make large sector wide reductions will be limited by the existing installed capacity of the fertilizer industry. Over time, changes should be possible as old plants are replaced by newer, more efficient and lower GHG emitting facilities.

Some of the largest differences in GHG emissions result from the application of the fertilizer and are mostly dependent on the natural environment. Individual producers can impact the quantity of N_2O generated by varying the timing of fertilizer application and by the use of slow release products but natural conditions will dominate these emissions and the differences from region to region.

There is still much to be learned about the N_2O production from fertilizer application and of the three regions investigated only Canada uses IPCC Tier 2 emission factors in its National GHG Inventory. The emission factors used here for the UK and Germany may be different than the actual factors in the field but, given the different moisture scenarios, it is highly likely that the N_2O emissions in the UK and Germany are in fact significantly higher than they are in Canada.

There are wide ranges in the emission factors used in many of the LCA tools but it has not been possible as part of this work to determine if the variation is real and reflects regional differences or if it is a function of using old, poorly documented data in the models that don’t reflect current operating conditions or a combination of the two issues.

8. MODELLING APPROACHES

The previous sections of the report have demonstrated that many of the important parameters that impact the biodiesel lifecycle GHG emissions are not constant but rather vary over time with showing improved performance with time. It has also been shown that there are some regional differences in agricultural performance and more importantly in the fertilizer sector and the local environmental conditions that very significantly impact the GHG emissions of biodiesel.

In this section some of the major models that are being used to access the GHG emissions of biodiesel, either from a regulatory perspective or a more scientific perspective are compared. The results of the models will be investigated to determine if the differences in the results can be accounted for by timing factors, the regional differences, or by model issues such as system boundaries or allocation methods.

8.1 RAPESEED

For rapeseed biodiesel the results from GHGenius for Canada are compared to the UK RFA Calculator, the BioGrace calculator, and the SenterNovem calculator. For this comparison the GHGenius results are presented on a lower heating value basis and the results are for the default values in the model. GHGenius also uses average values whereas the other tools use default values that are usually chosen to be higher than the average, so the comparisons are not perfect. The following summarizes the lifecycle results.

Table 8-1 Comparison of Model Results for Rapeseed Biodiesel

	GHGenius	UK RFA	SenterNovem	BioGrace
N fert rate, kg N/t	49.8	61.0	50.7	44.0
N_2O, % N applied[5]	1.0	2.0	2.1	2.3
Allocation	System Expansion	Energy	Energy	Energy
	g CO_2eq/MJ (LHV)			
Crop Production	38.0	52.1	65.6	49.0
Oil Extraction	4.4	4.5	4.7	7.6
Biodiesel	3.7	14.0	10.7	17.5
Other	1.5	2.7	0.7	1.6
Co-products				
Meal	-9.1	-18.2	-20.0	-23.2
Glycerine	-17.7	-0.0	-0.4	-0.8
Total	20.7	55.1	53.3	51.7

While the GHG emissions from the three European tools are relatively close in their final result, there are significant differences in the input assumptions and the individual stage results. The BioGrace model uses energy inputs that are 40% higher than the values found in the JRC well to wheels study for the oil extraction and biodiesel stages and that impacts the results, as can be seen in the previous table.

When they are compared to the GHGenius model, there are some significant differences. The lower feedstock production emissions in GHGenius are a function of less emission intensive nitrogen fertilizer manufacturing and lower N_2O emissions due to the local climatic

---

[5] Only the synthetic N fertilizer is used in the numerator. Excludes the N from crop residues.

and soil conditions as discussed in previous sections of the report. Only the SenterNovem tool provides transparency on how the N_2O emissions are calculated. It generally follows the 1996 IPCC guidance, except that it does not appear to calculate the contribution of the degrading straw. It does include the direct emissions (1.25% of N), the volatilization emissions (net 0.1% of N), and the emissions from leaching (30% leached and 2.5% converted for a net 0.75% of N). The 1996 guidelines use the 2.5% factor for N_2O emissions from leached nitrogen rather than the newer value of 0.75%, so this compensates for not including the emissions from straw.

There are large differences in the emissions from the biodiesel production stage between GHGenius and the other three tools. In the European tools the assumption is made that all of the carbon in the methanol is oxidized and assigned to the esterification step. Less than 5% of this oxidized carbon is then assigned to the co-product glycerine by the energy allocation method. In actual fact there is no oxidation of the carbon in the methanol until the biodiesel and the glycerine are oxidized during final use.

The carbon entering the biodiesel reaction is a combination of biogenic carbon from the rapeseed oil and fossil carbon from the methanol. The carbon leaves the system in the biodiesel and the glycerine. The oxidation of the biodiesel and the glycerine then creates CO_2. If both products were to be used as fuel (a reasonable assumption under the energy allocation approach) then the reference system would have CO_2 emissions from the combustion of diesel fuel and the fossil energy system that is used instead of the glycerine. The carbon balance is such that the carbon in the biodiesel is essentially equal to the carbon that was in the rapeseed oil and the carbon in the glycerine is equal to the carbon in the methanol. Since the glycerine replaces a fossil fuel, there will be CO_2 emissions in both the biodiesel system and the reference system and these emissions should probably not be counted against the biodiesel as they are in the European tools. This is one of the unintended consequences of using a non-system expansion approach to co-product allocation.

The system expansion methodology provides a much larger credit for the glycerine displacing synthetic glycerine production.

8.2 SOYBEANS

For soybean biodiesel, the same models are compared with the addition of three others, GREET, the California Air Resources Board Version of GREET, and the modeling that the US EPA did for RFS2. The later modeling effort was a consequential LCA rather than an attribution LCA. It modelled the changes in the GHG emissions in the world agriculture system as a result of increased demand for soybean biodiesel.

Table 8-2 Comparison of Model Results for Soybean Biodiesel

	GHGenius	UK RFA	SenterNovem	BioGrace	EPA RFS2	GREET 1.8d	CARB GREET
N fert rate, kg N/t	1.8	9.2	2.0	2.8	n/a	1.9	2.2
N_2O, % N applied[6]	39.3	9.1	2.1	27.9	n/a	10.5	8.9
Allocation	System Expansion	Energy	Energy	Energy	Consequential LCA	Displacement	Mass/ energy
	g CO_2eq/MJ (LHV)						
Crop Production	67.0	64.4	19.7	56.5	-17.9	14.2	29.8
Oil Extraction	11.7	15.4	13.7	24.3	13.9	21.3	21.0
Biodiesel	4.0	14.0	9.9	17.6	inc	4.6	5.2
Other	1.2	8.9	17.7	37.2	3.6	inc	5.0
Co-products							
Meal	-38.1	-43.3	-35.3	-77.6	inc	-31.4	-43.9
Glycerine	-17.7	-1.4	-0.4	-0.8	inc	-7.5	-0.3
Total	28.0	58.0	25.5	57.2	-0.4	1.2	16.8[7]

There is significant variation in the results for soybean biodiesel between the different tools and a large number of factors contribute to the difference. Soybeans fix most of their own nitrogen from the air and require very little synthetic nitrogen fertilizer but the soybean crop residues are high in nitrogen (although the exact nitrogen content is poorly documented in the literature) so that accounts for the high rate of N_2O as a percentage of synthetic nitrogen fertilizer applied. The SenterNovem calculator appears to have not included this source in their calculations. The UK tool has a very high rate of nitrogen applied.

The oil extraction values are impacted by the energy input and the carbon intensity of the energy. Some variation is expected given that the electric power carbon intensity will vary from location to location but there are also some significant variances in the thermal energy inputs. The impact of the 40% extra energy added in the BioGrace model is apparent in the table.

The other category includes transportation emissions. The BioGrace model has a scenario with very high transportation emissions. It is assumed that soybeans are transported 700 km by truck and over 10,000 km by ocean transport. The results would be very different if the soyoil was transported by ocean vessel. The allocation methodology allocates 65.6% of the freight emissions to the meal even though the meal accounts for over 80% of the mass and thus the emissions. The model does not have the flexibility to calculate the emissions when the oil is shipped rather than the beans.

The same issues with the methanol treatment that were identified for rapeseed biodiesel also apply here to the European tools.

---

[6] Only the synthetic N fertilizer is used in the numerator. Excludes the N from crop residues.

[7] Excludes 3.7 g CO_2eq/MJ that is deemed to arise from fossil carbon from methanol in biodiesel.

8.3 PALM OIL

For palm oil biodiesel the same models that were used for rapeseed biodiesel are compared. In all cases the models include the methane emissions from the effluent ponds but the values used vary considerably. There are some differences in the scenarios as to where the biodiesel production takes place, close to the plantations or close to the markets and this impacts the "other" category, as some transportation emissions are included in crop production in some cases.

Table 8-3 Comparison of Model Results for Palm Oil Biodiesel

	GHGenius	UK RFA	SenterNovem	BioGrace
N fert rate, kg N/t	10.3	5.3	4.1	6.7
N_2O, % N applied[8]	2.7	3.1	2.1	2.7
Allocation	System Expansion	Energy	Energy	Energy
	g CO_2eq/MJ (LHV)			
Crop Production	25.7	9.2	10.2	15.7
Oil Extraction	26.5	20.2	29.1	35.7
Biodiesel	2.6	14.0	10.6	17.6
Other	1.2	8.6	0.9	5.2
Co-products				
Meal	-0.5	-3.6	-5.0	-4.7
Glycerine	-17.6	-1.6	-0.4	-0.8
Total	36.8	46.8	45.4	68.7

The nitrogen fertilizer application rates also vary considerably with a variety of references used for the values. The methodological issues with methanol and glycerine are present for palm oil biodiesel.

8.4 WASTE GREASE BIODIESEL

The results from the four models, the US RFS2 analysis, and the CARB LCFS analysis using a modified GREET model are shown in the following table.

---

[8] Only the synthetic N fertilizer is used in the numerator. Excludes the N from crop residues.

Table 8-4 Comparison of Model Results for Waste Grease Biodiesel

	GHGenius	UK RFA	SenterNovem	BioGrace	EPA RFS2	CARB LCFS
Allocation	System Expansion	Energy	Energy	Energy	Consequential LCA	Energy
	g CO_2eq/MJ (LHV)					
Crop Production	0.0	0.0	0.0	0.0	0.0	0.0
Oil Extraction	1.8	0.0	0.1	1.1	0.0	4.9
Biodiesel	9.1	14.0	10.3	20.2	10.2	5.9
Other	1.5	0.2	0.2	1.3	3.7	0.8
Co-products						
Meal	0.0	0.0	0.0	0.0	0.0	0.0
Glycerine	-17.1	-1.4	-0.4	-1.2	Inc	-0.4
Total	-5.1	12.8	10.2	21.4	13.9	11.4

The reported values are relatively close; the BioGrace values are the highest reflecting the 40% penalty that the model applies to arrive at default values for processing stages. The different co-product application approaches and the methanol treatment account for other differences.

8.5 SUMMARY

There are some significant differences in the projected GHG emissions for the same biofuel from using different models and calculators. Some of these differences are caused by input differences that are only partially accounted for by regional differences in practices.

The methodology employed in all of the European models results in high emissions in the biodiesel production stage. This is caused by the assumption that all of the methanol is oxidized in the process. In actuality, some of the fossil carbon replaces some of the biogenic carbon in the feedstock but the biogenic carbon is present in the glycerine. The energy allocation approach used in these models does not consider the use of the glycerine nor the potential for the biogenic carbon in the glycerine to replace fossil carbon in the applications.

One of the issues that arise from the use of the energy allocation methodology is that there can be inconsistency between how the co-products are credited and the real world differences between the co-products from different feedstocks. Rapeseed meal contains 35-38% protein whereas soybean meal has 48-50% protein. In animal feed rations soybean meal is a much more valuable material but both materials have about the same thermal energy contents. In the following table the difference between the credit that rapeseed meal and soybean meal receives on a weight basis in the different models is shown.

Table 8-5 Co-product Valuation

	Rapeseed Meal	Soybean Meal	Rapeseed Meal	Soybean Meal
	$g\ CO_2eq/MJ$		$g\ CO_2eq/kg$	
UK RFA	18.2	43.3	323	346
SenterNovem	20.0	35.3	215	233
BioGrace	23.2	77.6	412	620

The RFA and SenterNovem models undervalue the soybean meal compared to its market value and feed displacement capabilities. The BioGrace model provides a reasonable credit for the meal based on its feed properties but that is a result of the carbon intensive scenario modeled rather than the model properties.

9. DISCUSSION AND CONCLUSIONS

There were three primary tasks involved with this work: the examination of emissions and their changes over time, an investigation of regional difference in GHG emissions, and a comparison of the results from various GHG models and calculators. The findings from each of these tasks are described below.

9.1 CHANGE IN EMISSIONS WITH TIME

Almost all of the parameters examined in feedstock production and major input production show trends towards reduced input intensity over time. In many cases this is driven by the trend towards higher crop yields, but there are other improvement factors that compound the rate of improvement. With this constantly changing, and improving picture on the inputs, it is not surprising that the GHG emissions for the production of biofuel are being reduced as time passes.

The available data on the supply chain for rapeseed and soybean biodiesel would indicate that the GHG emissions for these vegetable oil biodiesel fuels have decreased from 1995 to 2005, and if the present trends continue there should be further reductions in the emissions in the future. The emissions for rapeseed biodiesel have been declining at 1.9% per year and for soybean biodiesel at 0.6% per year. These rates may be conservative because the quality of the data for some parts of the supply chain has been poor. The results for rapeseed biodiesel are shown in the following table.

Table 9-1 Rapeseed Biodiesel GHG Emissions vs. Time

	Diesel Fuel	Rapeseed Biodiesel		
	1995	1995	2005	2015
	g CO_2eq/GJ (HHV)			
Fuel dispensing	131	150	157	122
Fuel distribution and storage	465	1,311	1,219	1,150
Fuel production	5,589	7,634	7,535	7,162
Feedstock transmission	1,015	949	956	980
Feedstock recovery	7,746	5,290	4,540	2,851
Land-use changes, cultivation	130	25,802	21,074	15,785
Fertilizer manufacture	0	11,743	9,743	7,981
Gas leaks and flares	3,221	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-126	-19,032	-20,784	-23,172
Sub-Total	18,170	33,846	24,441	12,860
Combustion Emissions	69,956	1,690	1,740	1,735
Grand Total	88,126	35,536	26,181	14,595
% Reduction		59.6	70.3	83.4

Looking forward, a number of potential improvements in the production practices of rapeseed and soybean production have been identified. Some of these innovations are already being implemented in various parts of the world and these trends should accelerate over the next decade. These innovations have the potential to reduce the emissions of rapeseed biodiesel by a further 29% and soybean biodiesel by almost 40%.

While the methodology used for these calculations is different than that used by the European Union for the GHG emission reductions required under the Renewable Energy Directive, the fact that there are reductions in GHG emissions over time should also become apparent once operators start to use actual data in the calculation of GHG emissions rather than using the default values in the RED. The reduction of more than 20 percentage points found in this work from 1995 to 2015 bodes well that the existing rapeseed biodiesel with a default GHG reduction of 38% will easily be able to meet the 50% reduction required in 2017 under the RED.

The findings with respect to the trends in biodiesel GHG emissions are generally consistent with the previous study ((S&T)^2, 2009) that looked at the emissions from corn ethanol production.

9.2 REGIONAL DIFFERENCE IN GHG EMISSIONS

The agricultural practices and GHG emission results for essentially the same crop are somewhat different in Canada, the UK and Germany. Germany benefits from high yield and good nitrogen fertilizer utilization and as a result the biodiesel produced there has the lowest GHG emissions when all other factors are held constant.

Much larger differences in GHG emissions have been identified from regional factors that are generally beyond the control of the feedstock producer. The production of nitrogen fertilizer is quite different from region to region, with different products being produced and different technologies being employed. European regions appear to use more nitrate-based fertilizers (ammonium nitrate, calcium nitrate, etc.) whereas in North America the ammonium-based fertilizers are more prevalent (ammonia and urea). There are large differences in the GHG emissions associated with the different types of fertilizers and this has a significant impact on the biodiesel lifecycle emissions.

While it is possible for individual feedstock producers to decide to switch types of fertilizer used and reduce the emissions associated with their production, the ability to make large sector wide reductions will be limited by the existing installed capacity of the fertilizer industry. Over time, changes should be possible as old plants are replaced by newer, more efficient and lower GHG emitting facilities.

Some of the largest differences in GHG emissions result from the application of the fertilizer and are mostly dependent on the natural environment. Individual producers can impact the quantity of N_2O generated by varying the timing of fertilizer application and by the use of slow release products, but natural conditions will dominate these emissions and the differences from region to region.

There is still much to be learned about the N_2O production from fertilizer application and of the three regions investigated only Canada uses IPCC Tier 2 emission factors in its National GHG Inventory. The emission factors used here for the UK and Germany may be different than the actual factors in the field but, given the different moisture scenarios, it is highly likely that the N_2O emissions in the UK and Germany are in fact significantly higher than they are in Canada. These results are summarized in the following table.

Table 9-2 Rapeseed Biodiesel GHG Comparison with Regional Factors

	Canada	UK	Germany
	g CO_2eq/GJ (HHV)		
Fuel dispensing	157	157	157
Fuel distribution and storage	1,219	1,219	1,219
Fuel production	7,535	7,535	7,535
Feedstock transmission	956	956	956
Feedstock recovery	7,609	5,326	4,312
Land-use changes, cultivation	13,985	42,334	24,770
Fertilizer manufacture	12,909	24,468	18,539
Gas leaks and flares	0	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-25,002	-9,425	-19,216
Total	19,369	72,571	38,273

There are wide ranges in the emission factors used in many of the LCA tools but it has not been possible as part of this work to determine if the variation is real and reflects regional differences or if it is a function of using old, poorly documented data in the models that don't reflect current operating conditions or a combination of the two issues.

9.3 MODEL COMPARISON

There are some significant differences in the projected GHG emissions for the same biofuel from using different models and calculators. Some of these differences are caused by input differences that are only partially accounted for by regional differences in practices.

The methodology employed in all of the European models results in high emissions in the biodiesel production stage. This is caused by the assumption that all of the methanol is oxidized in the process. In actuality some of the fossil carbon replaces some of the biogenic carbon in the feedstock but the biogenic carbon is present in the glycerine. The energy allocation approach used in these models does not consider the use of the glycerine nor the potential for the biogenic carbon in the glycerine to replace fossil carbon in the applications.

In the examination of the various models it was apparent that most models rely on a narrow set of reference material for choosing the input parameters. Not only are most of the sources 15 to 20 years old, but it is also not apparent how many of the parameters were arrived at. As economic operators begin to comply with the various sustainability criteria being put into regulation it is likely that regulators will find that the emissions for many stages of the lifecycles are significantly below the default values in the various tools and calculators that are available. While this is not expected to surprise the regulators that understand how the tools were developed, it may surprise many interested observers that the actual performance is so much better the models project. Careful communications will be required to educate the observers about how this situation arose.

Most of the models contain data and emission factors for major inputs into the biodiesel lifecycle stages that are beyond the direct control of the economic operators and will not be updated as operators move to comply with the new regulations. Emission factors for fertilizers, pesticides, and chemicals such as methanol need to be reviewed in many of the tools, as the current data is very old and poorly documented. Some calculators do not provide sufficient flexibility to account for the variation in producer inputs. One emission factor for nitrogen fertilizer is clearly inadequate to account for the various products and different production processes that are available.

There are also significant regional variations in emission factors caused by local environmental conditions and soil types that can impact the GHG emissions of biofuel feedstocks. The models and calculators need to have the flexibility to model these specific conditions accurately.

9.4 COMPARISON TO ETHANOL STUDY

In 2009, a similar study was undertaken for Task 39 ((S&T)^2 Consultants inc, 2009) looking at the expected change in GHG emissions for ethanol produced from corn. The GHG emissions for gasoline and ethanol from that study are shown in the following table. The emissions are presented on energy unit basis. For gasoline, the increase in energy use is mostly offset by the efforts to reduce fugitive emissions from operating wells. This has been the focus of significant efforts in Canada and other crude oil producing countries in recent years. The GHG emissions savings from ethanol production and use have more than doubled between 1995 and the projected level in 2015. This indicates the danger of making policy decision based on historical data without taking into account learning experiences and the potential gains that can be expected as industries develop. The GHG emissions reductions in 2015 from corn ethanol would qualify as advanced biofuels under proposed US regulations.

Table 9-3 Comparison of GHG Emissions - Gasoline and Ethanol

Fuel	Gasoline		Ethanol		
Feedstock	Crude Oil		Corn		
Year	1995	2015	1995	2005	2015
	g CO_2 eq/GJ (HHV)				
Fuel dispensing	118	90	185	181	142
Fuel distribution and storage	656	507	1,107	1,109	1,124
Fuel production	11,181	12,162	35,012	28,294	19,085
Feedstock transmission	1,084	903	1,004	1,009	1,031
Feedstock recovery	7,257	8,724	12,012	10,550	7,348
Land-use changes, cultivation	8	15	21,827	20,987	20,369
Fertilizer manufacture	0	0	8,261	7,033	6,215
Gas leaks and flares	3,486	1,688	0	0	0
CO_2, H_2S removed from NG	0	0	0	0	0
Emissions displaced	-65	-137	-18,490	-17,934	-17,219
Sub-Total	23,725	23,951	60,919	51,229	38,095
Combustion emissions	62,917	64,813	3,058	2,237	1,973
Grand Total	86,642	88,764	63,977	53,466	40,068
% Reduction			26.2	39.0	54.9

Between 1995 and 2015 it is expected that the GHG emissions will be reduced by 28.7 percentage points. For the same period this work found a similar trend but a slightly lower magnitude of change with rapeseed biodiesel GHG emissions being reduced by 23.8 percentage points.

There are significant differences in the two lifecycles and one shouldn't expect the reductions to be identical. One of the differences in the two systems is the amount of energy (and thus the GHG emissions created) used in the fuel production process. Much more energy is used to manufacture ethanol than biodiesel and the ethanol industry has a well demonstrated history of reducing the emissions, whereas there is little evidence of similar reductions in the biodiesel production process.

10. REFERENCES

(S&T)^2 Consultants Inc. 2009. An Examination of the Potential of Improving Carbon/Energy Balances for Bioethanol. http://www.task39.org/LinkClick.aspx?fileticket=M35hgy3JDEI%3d&tabid=4426&language=en-US

AEA Technology plc. 2010. UK Greenhouse Gas Inventory, 1990 to 2008. http://unfccc.int/files/national_reports/annex_i_ghg_inventories/national_inventories_submissions/application/zip/gbr-2010-nir-27may.zip

Agriculture and Agri-Food Canada. 1999. Data from Research Centres at Swift Current, Indian Head, Melfort, Tisdale, Lethbridge, and Rycroft. Unpublished.

Agriculture and Agri-Food Canada. 2001. Opportunities for Reduced Non-Renewable Energy Use in Canadian Prairie Agricultural Production Systems. http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1196192081908&lang=eng

Berghout, N. 2008. Technological Learning in the German Biodiesel Industry. http://www.chem.uu.nl/nws/www/publica/Publicaties%202008/NWS-S-2008-12.pdf

Bernesson, S. 2004. Life Cycle Assessment Of Rapeseed Oil, Rape Methyl Ester And Ethanol As Fuels - A Comparison Between Large- And Small-scale Production. http://pub-epsilon.slu.se:8080/436/01/SLU_BT_R2004_01_LCA_ro_RME_ethanol_Sven_Bernesson.pdf

BioGrace. http://www.biograce.net/

Brentrup, F., Palliere, C. 2008. GHG Emissions and Energy Efficiency in European Nitrogen Fertiliser Production and Use. The international Fertiliser Society. Proceedings No: 639.

Brimner, T., Gallivan, G., Stephenson, G. 2005. Influence of Herbicide-Resistant Canola on the Environmental Impact of Weed Management. Pest Management Science. Vol 61, No. 1. 47-52. http://dx.doi.org/10.1002/ps.967

Canadian Fertilizer Institute. 2009. Fertilizer Shipments to Canadian Agricultural Markets. Cumulative Fertilizer Year July 2009 - December 2009. http://www.cfi.ca/_documents/FSS%20Q2_%202009-10%20pub_E.pdf

Canola Council. 2001. An Agronomic and Economic Assessment of Transgenic Canola. http://www.canolacouncil.org/uploads/biotechnology/manual/GMO/final.zip

Cheminfo Services. 2008. Sensitivity Analysis of Most Common Bioethanol LCA Models to Determine Assumptions with Greatest Influence on Outputs. Prepared for Environment Canada. March 2008. http://www.ghgenius.ca/reports/BioethanolLCAFinalReport.pdf

Department for Environment, Food and Rural Affairs. 2010. Agriculture in the United Kingdom 2009. http://www.defra.gov.uk/evidence/statistics/foodfarm/general/auk/latest/documents/AUK-2009.pdf

Department for Environment, Food and Rural Affairs. 2010b. The British Survey of Fertiliser Practice 2009. http://www.defra.gov.uk/evidence/statistics/foodfarm/enviro/fertiliserpractice/documents/2009.pdf

Downs, H., Hansen, R. 1998. Estimating Farm Fuel Requirements. http://www.ext.colostate.edu/pubs/farmmgt/05006.pdf

EFMA. 2010. Nitrogen Fertilizer Consumption in EU 27 2006/07. http://www.efma.org/documents/file/statistics/consumption/Nitrogen%20Fertilizer%20Consumption%20in%20EU%2027%202006%2007.jpg

Environment Canada. 2010. National Inventory Report 1990-2008. http://unfccc.int/files/national_reports/annex_i_ghg_inventories/national_inventories_submissions/application/zip/can-2010-nir-15april.zip

Farrell, A. E., and Sperling, D. August 1, 2007. A Low-Carbon Fuel Standard for California. Part 1: Technical Analysis. http://www.energy.ca.gov/low_carbon_fuel_standard/UC-1000-2007-002-PT1.PDF

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M., Kammen, D., 2006. Ethanol can Contribute to Energy and Environmental Goals. Science, 311:506-508.

Fleming, J.S., Habibi, S., MacLean, H.L. 2006. Investigating the Sustainability of Lignocellulose - Derived Light-Duty Vehicle Fuels through Life Cycle Analysis. Transportation Research Part D: Transport and Environment. 2006. 11. 146-159.

German Federal Environment Agency. 2010. National Inventory Report For the German Greenhouse Gas Inventory 1990 – 2008. http://unfccc.int/files/national_reports/annex_i_ghg_inventories/national_inventories_submissions/application/zip/deu-2010-nir-12may.zip

HGCA. 2005. Environmental Impact of cereal and Oilseed rape for Food and Biofuels in the UK. http://www.hgca.com/document.aspx?fn=load&media_id=1909&publicationId=2309

International Standards Organization, ISO 14040:2006 - Environmental Management - Life cycle assessment - Principles and framework, 2006; www.iso.org/iso/iso_catalogue (ISO 14040:2006).

IPCC. 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/gl/invs6.html

IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

IRENA. IRENA 08 – Mineral fertiliser consumption. http://eea.eionet.europa.eu/Public/irc/eionet-circle/irena/library?l=/final_delivery/indicator_sheets&vm=detailed&sb=Title

JRC. WTW Results Version 3. http://ies.jrc.ec.europa.eu/jec-research-collaboration/downloads-jec.html

Kim, S., Dale, B., 2002. Allocation Procedure in Ethanol Production System from Corn Grain. International Journal of Life Cycle Assessment. Volume 7. Pages 237-243.

Kongshaug, G., Jenssen, T. 2003. Energy Consumption And Greenhouse Gas Emissions In Fertilizer Production. International Fertiliser Society Meeting. London, UK. 3rd April 2003. http://www.fertilizerseurope.com/PRODUCT%20STEWARDSHIP%20PROGRAM%2008/images/IFS%20Energy%2003%2004%202003.doc

Larson, E. D. A review of life cycle analysis studies on liquid biofuel systems for the transport sector. Energy for Sustainable Development. Vol. X No. 2. June 2006. p. 109-126.

McConkey, B., Dyer, J., Vergé, X., Cerkowniak, D., Desjardins, R,, and Worth, D. Including Carbon Stock Change From Land-use and Land Management in the Greenhouse-gas LCA of Crops. Presented at LCA FOOD 2010. September 2010, University of Bari (Italy)

Moerschener, J. and Lucke, W. 2002. Energy Investigations of Different Intensive Rape Seed Rotations – A German Case Study. Economics of Sustainable Energy in Agriculture, Economy & Environment 24. Kluwer Academic Publishers b.v. Dordrecht, The Netherlands, 27-40.

Monsanto. 2009. Monsanto Company 2008-2009 Corporate Responsibility and Sustainability Report. http://www.monsanto.com/SiteCollectionDocuments/2008-2009-csr-report.pdf

Mortimer, N., Cormack, P, Elasyed, M. Horne. R. 2003. Evaluation of the Comparative Energy, Global Warming and Socio-Economic Costs and Benefits of Biodiesel. www.ienica.net/usefulreports/sheffield.pdf

Nagy, C. 2010. Personal communication. Canola Energy Data.

National Biodiesel Board. 2009. Comprehensive Survey on Energy Use for Biodiesel production. http://www.biodiesel.org/pdf_files/fuelfactsheets/Energy_Use_Survey.pdf

NL Agency. 2010. Greenhouse gas emissions from cultivation of maize, rapeseed, sugar beet and wheat for biofuels. Report number GAVE-10-02. http://www.senternovem.nl/mmfiles/GAVE-10-02_NUTS-2_report_Netherlands_tcm24-338757.pdf

NRCan. 2007. Canadian Ammonia Producers - Benchmarking Energy Efficiency and Carbon Dioxide Emissions. http://oee.nrcan.gc.ca/publications/infosource/home/index.cfm?act=online&id=5972&format=PDF&lang=01

Patyk, A., Reinhardt, G. 1996. Düngemittel - Energie- und Stroffstrombilanzen.

PAV, 2000, Quantitative information "KWIN" 2000/2001 - Agriculture and vegetable cultivation (in Dutch), Practice research for agriculture and vegetable cultivation PAV, Lelystad the Netherlands.

Schmidt. J. 2007. Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil. http://people.plan.aau.dk/~jannick/Publications/Thesis_part3.pdf

SenterNovem. GHG Tool. http://www.senternovem.nl/gave_english/ghg_tool/index.asp

State of California Office of the Governor. Executive Order S-1-07, The Low Carbon Fuel Standard. January 18, 2007.

Statistics Canada. 2006 Census of Agriculture. Land use, tenure, and land management practices. http://www.statcan.gc.ca/pub/95-629-x/2007000/4182415-eng.htm

The Food and Environmental Research Agency. 2010. Pesticide Usage Statistics. http://pusstats.csl.gov.uk/myindex.cfm

The Keystone Center. 2009. Field to Market: The Keystone Alliance for Sustainable Agriculture Environmental Resource Indicators for Measuring Outcomes of On-Farm Agricultural Production in the United States First Report, January 2009. http://keystone.org/files/file/SPP/environment/field-to-market/Field-to-Market_Environmental-Indicator_First_Report_With_Appendices_01122009.pdf

UK RFTO. RFA Carbon Calculator. http://www.renewablefuelsagency.gov.uk/carboncalculator

UN FAO. 2010. Statistics. http://faostat.fao.org/

Unilever. 2007. Sustainable Winter Oilseed Rape. http://www.biofuelstp.eu/downloads/042007_Unilever_OSR_English.pdf

United Kingdom Department of Transport 2006. Renewable Transport Fuel Obligation Programme (RTFO). www.dft.gov.uk/roads/RTFO

United States Department of Agriculture. 2010. Foreign Agricultural Service. Production, Supply and Distribution Online. http://www.fas.usda.gov/psdonline/psdHome.aspx

USDA. 2004b. Energy Use by Crop and State. http://www.ers.usda.gov/data/costsandreturns/Fuelbystate.xls

USDA. Fertilizer Use. http://www.ers.usda.gov/Data/FertilizerUse/Tables/FertilizerUse.xls