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**OPPORTUNITIES FOR REDUCING GREENHOUSE GAS EMISSIONS BY
USING ETHANOL-BASED FUELS: AN EASTERN ONTARIO (CANADA)
CASE STUDY OF THE POTENTIAL FOR GRAIN CORN PRODUCTION**

by

Gary Vandergaast, B.Sc.

A thesis submitted to the Faculty of Graduate Studies in partial fulfillment of the
requirements for the degree of

Master of Arts

Department of Geography and Environmental Studies

Carleton University

Ottawa, Ontario

September 1999

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Thesis Supervisor

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CARLETON UNIVERSITY

September 1999

Abstract

Ethanol produced from corn has the potential to reduce greenhouse gas emissions when used as an automotive fuel. A linear programming model representing Eastern Ontario's agricultural system was developed to assess the region's potential to produce grain corn for conversion to ethanol. Under a scenario where recent regional agricultural production trends were projected fifteen years into the future, the maximum theoretical potential is an additional 1.42 million tonnes of corn annually. Corresponding emission reduction benefits are estimated to be 0.3 to 0.6 Megatonnes CO₂ equivalent per year. This equates to 45% to 85% of the region's share of the reductions required for the cars and light trucks sector to meet Canada's Kyoto Protocol objectives. Greater contributions are possible if other crop production demands are lessened. Additional studies are needed to go beyond this land resource based study and to determine the actual practical extent that an ethanol strategy could or should contribute to Canada's climate change strategy.

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Finally, I thank God for everything!

Opportunities for Reducing Greenhouse Gas Emissions by Using Ethanol-based Fuels: An Eastern Ontario (Canada) Case Study of the Potential for Grain Corn Production

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1 INTRODUCTION

1.1 NATURE OF THE PROBLEM

Accelerated global climate change is considered by many to be one of the most pressing issues facing humanity at the close of the twentieth century. From about the beginning of the 1990s, there has been a general consensus within the scientific community that the climatic changes now being observed worldwide are indeed the result of the radiatively active gases (more commonly called greenhouse gases) that have been added to the atmosphere by way of various human activities since the start of the industrial revolution (IPCC, 1996). Furthermore, global climate change due to the enhanced “greenhouse effect” and its impacts on human populations and planetary ecosystems are expected to become more pronounced during the early centuries of the next millennium, especially if emissions of greenhouse gases continue to increase or are not substantially reduced (IPCC, 1996).

Addressing the climate change issue has been the focus of much international attention and consultation involving both the scientific community and the policy-making agencies of governments. For example, the Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization and the United Nations Environmental Program (UNEP) in 1988 to provide an authoritative international statement of scientific opinion on climate change, including its causes, impacts and possible response strategies. The conclusion that there is now clear evidence for a discernable human influence on global climate (IPCC, 1996) has underscored recent calls for the mitigation of anthropogenic greenhouse gas emissions. A principal strategy suggested for industrialized nations

to mitigate the potential effects of climate change is through reducing greenhouse gas emissions at the source.

The United Nations developed the Framework Convention on Climate Change (FCCC) agreement which was signed by 154 countries, including Canada at the Earth Summit in Rio de Janeiro, Brazil in June 1992. Under the agreement, Canada, as a developed country, agreed to try to reduce greenhouse gas emissions to 1990 levels by the year 2000. However, by the latter part of the present decade it was already clear that Canada would not be able to meet this initial greenhouse gas emission reduction target.

Among other things, the FCCC also instituted a process that called for regular meetings of signatory governments. The Conference of the Parties (COP) i.e., those countries that signed the FCCC, meets once a year to review progress on attaining emission reduction targets. Following the COP conference held in Kyoto, Japan in December 1997, Canada signed the Kyoto Protocol, an agreement which commits it to reducing greenhouse gas emissions to a level which is 6% below the emissions total for 1990 sometime during the period 2008 to 2012¹ (Natural Resources Canada, 1998).

Fundamentally, climate change is an unavoidable circumstance of living on this planet. Cycles of climatic change, manifest as discernable trends in the normal, average climate, are known to have occurred at various time scales throughout earth

¹ Throughout this thesis, the Kyoto Protocol time frame will be simplified to 2010. i.e., the mid-point of this formally stated range.

history (see Section 2.5). However, a major concern with the prospect of global climate change at present – one induced by human activity – is that it is likely to have negative consequences because it is taking place over a much shorter than normal time scale. Accordingly, populations and ecosystems may not have time to adjust or adapt to the changes without substantial human suffering or unhealthy ecosystem impacts (e.g., species extinction, loss of bio-diversity, etc.).

Although Canada's greenhouse gas emissions result primary from the industrialized nature of our society, there are two factors that significantly affect the level of greenhouse gas emissions, both of which are related to our geography. Our northern-latitude location on the globe means that a major concern is heating our homes, offices, schools, etc. during the winter season. Our large land area and relatively low-density population are fundamental factors leading to transportation being the greatest single contributor of greenhouse gas emissions in Canada. The transportation sector contributed about 27% of the country's greenhouse gas emissions in 1995 (Environment Canada, 1997a). Of this amount, approximately one third is associated with the combustion of fossil fuels in personal automobiles. Such a single large contributor is therefore an obvious target and key to overall greenhouse gas emission reduction strategies in Canada.

Canada's federal, provincial and territorial Environment and Energy Ministers approved the creation of a National Climate Change Secretariat in April of 1998 to coordinate the national effort for identifying solutions that will have a positive impact on reducing greenhouse gas emissions. The approach of the Secretariat in this respect was to establish a number of expert committees called Issue Tables to identify

and assess greenhouse gas reduction opportunities in their respective sectors. The foundation paper from the Transportation Table – National Climate Change Process (1998) identifies three broad areas where greenhouse gas emissions may be reduced in the transportation sector. These are as follows:

- Reducing fuel consumption, either by
 - improving engine combustion efficiency or
 - changes in transportation activities (e.g., more use of public transit or otherwise voluntarily driving less).
- Switching to power train technologies that avoid or minimize the combustion of fossil fuels (e.g. electricity or fuel cells).
- Substituting for fuels that have lower greenhouse gas emissions (e.g. ethanol-blend fuels).

As noted above, one possible greenhouse gas emission reduction strategy in the transportation sector is to increase use of ethanol-blend fuels. The benefit of reducing greenhouse gas emissions by using ethanol-blend fuels arises because the carbon content can be considered a renewable source. In the context of the global carbon cycle, using biomass-derived ethanol for fuel eliminates the release of carbon by the combustion fossil of fuels derived from the long-life, deep geological carbon reservoir. As long as the net carbon balance is positive, a net benefit will result. This means that the carbon from the fossil fuels used to produce the ethanol must not exceed the carbon content of the ethanol on an energy equivalent basis.

Determining the carbon balance for producing and using various fuel alternatives is a complex procedure. During the past 10 years or so, there has been a substantial volume of research devoted to conducting such carbon/energy balance determinations by means of total fuel cycle modeling. Some early work showed a net negative carbon balance, with more fossil fuel input required than the equivalent energy content of the ethanol produced (e.g., Ho and Renner, 1990; Pimentel, 1991). However, as refinements were made in the development of various fuel cycle models, and as ethanol production technologies have improved in response to a growing demand for fuel ethanol, it is more generally concluded that the net carbon balance for ethanol will be positive (e.g., Wang et al., 1997; Shapouri et al., 1995). Although such studies have not yet fixed on a definitive value – there remain many uncertainties and the modeling is an extremely complex activity – the use of ethanol-blend fuels now appears to offer significant promise as a means of reducing greenhouse gas emissions.

At present, these fuels are primarily used in light-duty gasoline automobiles and light-duty gasoline trucks². Although the use of ethanol-blend fuels in Canada has increased substantially since the early 1990s, there currently still appears to be substantial opportunity for increasing its share of fuel sales. Based on Natural Resources Canada (1997) estimates, ethanol comprised approximately 0.15% of the volume of all motor fuel used in automobiles and light trucks in 1995. By the year 2000, it is projected that Canada's total ethanol production capacity will have

² This includes primarily pickup trucks, vans, minivans, and sport utility vehicles. Together with automobiles, they consume more than 95% of non-diesel road transportation fuel (Environment Canada, 1997a).

expanded to the extent that it could supply about 1.8% of these automotive fuel requirements³ (see Section 3.2). In this context, it may be concluded that there is a potential for ethanol's contribution to motor fuel requirements to be increased even further – say to 5% or 10% as a start – in the immediate future. In order to increase the benefit of ethanol as a greenhouse gas reducer to such an extent, substantially increased quantities of the feedstock for ethanol production will be required. Within the 2010 time frame of the Kyoto Protocol, the most likely feedstock for ethanol production will continue to be grain (in Western Canada) or corn (in Eastern Canada). Increased production of ethanol would therefore create additional or competing demands for land for these agricultural purposes.

Searches for alternative fuels in response to the OPEC oil crisis of the 1970s did stimulate some research into agricultural land requirements for biomass feedstock and possible conflicts between land use for bio-fuel production and food production (e.g., Cocklin, 1985). With the recent major interest in developing greenhouse gas mitigation strategies, it may be expected that interest in assessing the ability of agricultural systems to produce adequate levels of feedstocks for ethanol production may also be heightened and to become increasingly relevant. Whereas ethanol-blend fuels show considerable promise in this respect, it looks as though the majority of the on-going research into the potential for ethanol as a bio-fuel, even up to the present, focuses on technology-related issues of producing ethanol from agricultural products and on issues related to the identification and culture of crops which would be

³ The large majority of existing and new production capacity expected to be available by the end of 2000 is intended for automotive fuel use. A small fraction continues to be produced for other industrial uses.

suitable feedstock material for a large-scale ethanol industry (e.g., Stumborg, 1998; Agriculture and Agri-Food Canada, 1997). It seems that the capacity of the land base to specifically support this greenhouse gas mitigation strategy while simultaneously meeting future food demands has not been explored to any great extent, especially at the regional level.

1.2 PURPOSE AND OBJECTIVES

The purpose of this thesis is to examine the prospects for substantially increasing Eastern Ontario's level of grain corn production in the context of a potentially rapid and substantial increase in future demands for ethanol as an alternative transportation fuel. In this respect, the thesis will evaluate the extent to which the available land resources in Eastern Ontario are theoretically able to support significant increases in ethanol production and hence its ability to contribute to strategies for reducing greenhouse gas emissions consistent with the objectives specified for Canada in the Kyoto Protocol. Eastern Ontario is chosen as a case study to demonstrate one approach for tackling this important issue. The region is currently a major contributor to Ontario's agricultural economy, including substantial grain corn production (OMAFRA, 1996) and there is some evidence that regional agricultural production levels could be increased (LEG, 1984).

It is certainly to be expected that the agricultural land base will also be required to simultaneously satisfy existing and continuing demands for the present production of grain corn as well as other crops. The issue may therefore be cast as one of defining the optimum use for a scarce resource, the land base in this case, and one that can

be addressed by quantitative analytical techniques such as linear programming.

Because of uncertainties concerning future ethanol production technologies and in the area of how competing demands will be met, it is useful to consider a number of different scenarios that depict a range of possible futures. For the purposes of this research, three scenarios, which are considered comprehensive in that they reflect a plausible spectrum of ethanol's potential contribution to reducing greenhouse gas emissions in the transportation sector, will be evaluated as follows:

- a) a conservative estimate of ethanol production providing a 5% market share, on an energy equivalent basis, of the fuel demand for cars and light trucks.
- b) a more aggressive ethanol strategy involving a 10% renewable energy-content market penetration.
- c) a radical shift to ethanol fuel with a 50% by volume share of all automobile/light truck fuel requirements. At this level, this component of the transportation sector could reduce greenhouse gas emissions to 6% of its 1990 level.

In order to provide a response to the questions implicit in the purpose of this thesis, the principal objectives of the ensuing feasibility assessment are expressed in the following three points:

- a) to describe the nature and extent of the climate change problem,

- b) to examine the potential role that ethanol may be able to play in reducing greenhouse gas emissions and
- c) to determine Eastern Ontario's potential to support ethanol-for-fuel production facilities via grain corn production.

1.3 SCOPE OF RESEARCH PROGRAM

The research in this thesis constitutes a feasibility study of the potential for grain corn in Eastern Ontario to contribute to reductions in greenhouse gas emissions by using ethanol fuel in automotive transportation. As such, it constitutes but one component of a larger overall undertaking that may involve quite a number of other relevant studies that would need to be completed prior to making a decision on whether to employ this strategy as part of a national, provincial or regional greenhouse gas mitigation program.

The feasibility study specifically focuses on the question of what is technically possible within the regional agricultural land resource base with respect to producing large quantities of grain corn. As such, it can identify the maximum level of production that could theoretically be accommodated within the available resources under various use scenarios. It is also expected that it can provide a fair indication of the scope of what may actually be achieved in this respect. For example, are the prospects substantial, trivial or somewhere in between? On these two points, the results of this work are expected to be particularly pertinent.

One of the more significant consequences of the distinguishing nature of this study is that specific and comprehensive economic considerations are not expressly relevant to conducting the analysis. With the fundamental objective of identifying the extent to which grain corn could be produced, not how much can in fact be produced or how much ought to be produced, one can avoid the added complexity that would result if the particular socio-economic factors that normally govern agricultural activity were to be required for this feasibility-level analysis.

Once the fundamental level of feasibility is determined, it would be appropriate to initiate subsequent studies and assessments aimed at determining what should in fact be attempted and at identifying all that would be required to move ahead with the ethanol option. This research can therefore be considered an important and a preliminary step in a larger overall process. Some of the other kinds of studies or assessments that would also be required in this context are enumerated in the concluding section of the thesis.

1.4 THESIS OUTLINE

This thesis consists of five main sections. Section 2 provides a synopsis of the current scientific understanding in a number of areas relevant to the subject of climate change and greenhouse gas emissions. Its primary purpose is to frame the proposed research within an appropriate context. Although the review is epigrammatic by necessity, it is intended to systematically make the case for the significance of assessing the prospects for growing sufficient grain corn in Eastern Ontario to meet a potentially increasing demand for fuel ethanol at this time. The

review includes six main topic areas, starting with the subjects of 1) what constitutes climate change; 2) greenhouse theory and atmospheric science; 3) evidence of increasing greenhouse gas emissions; and 4) greenhouse gas sources. It then discusses and presents evidence of climate change and general mitigation/adaptation issues, including potential impacts on agriculture. Lastly, Section 2 discusses potential mitigation strategies that may be implemented in the transportation sector for reducing emissions.

In Section 3, the potential role of ethanol as an essential component of Canada's greenhouse gas mitigation strategies is described. The use of ethanol as a transportation fuel, its production and usage and its ability to contribute to reduced greenhouse gas emissions are explained.

Section 4 gives a geographic overview of Eastern Ontario and focuses on selected aspects of the agricultural scene in the region. It also provides an in-depth assessment of trends and changes in land use patterns observed in the region during the last 15 to 25 years. These analyses are important because they help determine the input data needed for the agricultural land use model.

Section 5 outlines the framework within which the present regional case study is to be carried out. It describes the linear programming methodology as well as the specific land use model developed for Eastern Ontario that will be used to assess the prospects for the three ethanol scenarios. In addition, Section 5 outlines the model's implementation by describing selected future scenarios within which ethanol may become an important contributor to achieving greenhouse gas reductions. Lastly,

Section 5 presents all the input data requirements for the model along with a description of the respective data sources and derivations, the rationale for their use in the model and any other general assumptions regarding either the structure of the model or the selected data inputs.

The presentation and analysis of the modeling results comprise Section 6. The thesis concludes with a summary response to the question(s) posed by the objectives of the research project. As such, it will outline the degree to which grain corn production, and hence ethanol production, can be increased in Eastern Ontario to meet a potentially increasing demand for alternative, renewable energy source automotive fuel, while at the same time maintaining the levels of all existing and continuing demands for agricultural products. This will be done in the context of assessing the potential relative contribution that ethanol can make to Canada's overall greenhouse gas mitigation strategies.

2 GLOBAL CLIMATE CHANGE

2.1 CLIMATE AND CLIMATE CHANGE

This section addresses the question, “What constitutes a changing climate”? Climate is often defined as simply the “average weather” experienced in a given region over an extended period. In the context of climate change however, this definition is inadequate because it excludes consideration of year to year variability. The variability of a particular meteorological parameter could change while the average does not change appreciably. For example, there could be more frequent and/or more severe temperature extremes. In addition, such a definition does not specify a time scale over which an average should be determined. Although the notion of an average or normal climate implies a steady state system, history and scientific evidence suggest that even over such relatively short periods as a few decades, climate is anything but steady state. In fact, climate varies at all time scales, in response to both periodic or random forcing factors (Goodess et al., 1992).

By the early 1980s, a well-developed theory⁴ had been advanced that relates periodicity elements of the earth’s orbit, which affect the amount of solar radiation received, to cycles of warmer and colder climates as inferred by various geologic or palaeoclimatic evidence. For example, oxygen isotope studies of deep-sea sediment cores have shown periodic variations in the ratio of ¹⁸O to ¹⁶O that coincide with the

⁴ The basic Milankovitch Theory (1941) includes three primary elements: 1) variable axial obliquity with an average periodicity of about 41,000 years, 2) axial precession with average periodicity values of 19,000 and 23,000 years and 3) orbital eccentricity variations with an average periodicity of 95,000 years (Goodess et al., 1992).

three Milankovitch cycles (Goodess et al., 1992). During colder periods, less ^{18}O is evaporated from the oceans. This enriches ocean water, and hence calcareous sediments, in ^{18}O while glacial ice is enriched in ^{16}O . Other research has led to the conclusion that besides the orbital forcing factors, climate also responds to internal feedback mechanisms such as changing concentrations of atmospheric greenhouse gases, the ice-albedo feedback, changes in ocean circulation patterns and others (Goodess et al., 1992). Nevertheless, Goodess et al. (1992) concluded that orbital forcing is the major cause of the glacial-interglacial cycles inferred for the Quaternary Period. It is not intended to discuss this topic in further detail in this thesis – the reader can find a good review in Goodess et al. (1992). Rather, the objective here is to highlight the conclusion that there seems to be good evidence of periodic climatic changes in response to natural mechanisms operating over very long time scales.

Since the last glacial maximum approximately 18,000 years ago, there have been at least four occasions of significant shorter time scale deviations of the climate from antecedent conditions (Gribben and Lamb, 1978). These are 1) the post-glacial warming period commonly referred to as the Holocene optimum from about 5000 to 3000 BC, 2) the Iron Age cold epoch from about 900 to 300 BC, 3) the Medieval warm epoch from about 1000 to 1300 AD and 4) the “Little Ice Age”, a cooling period from about 1430 to 1850 AD. Cause and effect relationships to explain these events as well as other shorter-term variations superimposed on them are very complex and appear to be linked to a number of factors such as natural changes in ocean circulation, solar variability, changes in the level of volcanic activity, changes in atmospheric greenhouse gas concentrations and the effects of fluctuating air-sea-ice-land feedbacks and ocean-atmosphere feedbacks (Goodess et al., 1992).

There does not appear to be a generally accepted “standard” for what constitutes a climate change, either in terms of the time scale or in terms of the magnitude. However, even a global average temperature rise of only 1 K is predicted to have significant environmental impacts such as more extremes in local weather (Environment Canada, 1991). In this context then, the current warming trend being attributed to increased concentrations of greenhouse gases in the atmosphere (see Section 2.5), may be classified as a short term climate change phenomenon. Fundamentally, this trend may therefore be considered not all that different from other warming periods experienced in the past. However, an important distinguishing difference is that the current effect is almost certainly being caused by relatively recent human activity (IPCC, 1996). Moreover, the time frame within which the change seems to be taking place is such that over a period of some decades to a century or so, the potential impacts of a changing climate on global agricultural and economic systems are not likely to be inconsequential.

Another factor affecting shorter-term climatic variations is related to the fact that the global climate system is very complex and that the determination of climate seems to include a stochastic element due to the turbulent nature of atmospheric processes. Consequently, and in view of the foregoing discussion, it can be concluded that a propensity to change may be considered a basic characteristic of the earth’s climate system (Environment Canada, 1991). A pertinent question in this respect is how much change would be considered acceptable or tolerable by human populations. Some reflection on this is presented in Section 2.5.

2.2 GREENHOUSE THEORY AND ATMOSPHERIC SCIENCE

Recent climate modeling efforts have shown that there is an approximately linear relationship between the global mean change in net irradiance ($\Delta F \text{ W m}^{-2}$) at the tropopause⁵, also referred to as *radiative forcing*, and the equilibrium global mean surface temperature change ($\Delta T_s \text{ K}$) such that:

$\Delta T_s = \lambda \Delta F$ where λ is a climate sensitivity parameter (Shine et al., 1994). The degree of radiative forcing may be affected by three principal factors as follows:

- the radiative output of the sun,
- greenhouse gas concentrations, which result in positive changes in ΔF when concentrations increase and
- the respective quantities of tropospheric and stratospheric aerosols, which result in negative changes in ΔF when levels increase.

Low concentrations of naturally occurring greenhouse gases in the earth's atmosphere act by trapping a portion of the infrared radiation that is emitted by land and water surfaces after they have initially absorbed incident solar radiation. This natural and essential "greenhouse effect" causes the surface and the lower

⁵ The definition of radiative forcing specifies that ΔF is determined after allowing for stratospheric temperatures to re-adjust to radiative equilibrium, but with surface and tropospheric temperatures held constant at pre-perturbation levels (Shine et al., 1994).

atmosphere to warm by about 33 K (from about -18°C to about 15°C) and therefore results in conditions favorable for biological life. The naturally occurring greenhouse gases include water vapor, ozone, carbon dioxide, methane and nitrous oxide. The latter three are important because human activity is leading to increased concentrations in the atmosphere. According to the above relationship, this implies that greater levels of radiative forcing and a concomitant increase in the global mean surface temperature may be expected.

Quantitatively, carbon dioxide (CO₂) is by far the most important greenhouse gas. It occurs in the atmosphere as part of the global carbon cycle (see Figure 2.1). This cycle consists of four major carbon reservoirs: the atmosphere, the oceans, the terrestrial biosphere (living plant/animal material as well as soils and detritus) and the geosphere (rock formations, deep sediments, and fossil fuel deposits) with natural exchanges, or fluxes, between these reservoirs taking place on various time scales⁶. For example, the process of photosynthesis transfers about 120 billion tonnes of carbon from the atmosphere to the biosphere annually. An approximately similar quantity of carbon is re-released to the atmosphere each year through respiration and/or heterotrophic decay. Longer-term cycles, from hundreds to in the order of a thousand years, include the carbon incorporated into long-lived biota, the soil or the deep water of the ocean. Very long time scale components of the cycle include fossil fuel deposits, carbon in geologic materials, and carbon tied up as methane in marine sediment clathrates.

⁶ Saying that exchanges between components of the carbon cycle occur at different time scales really means that they are quantitatively significant only at a particular time scale.

Figure 2.1: The Global Carbon Cycle

Numbers in boxes represent reservoirs of carbon (billions of tonnes) and numbers between boxes represent fluxes of carbon in billions of tonnes per year.

Source: Environment Canada (1991), based on MacDonald (1990).

This kind of view of the carbon cycle could give the impression that the quantities shown for the major reservoirs remain constant with time. This however, is usually not the case, especially when sufficiently long periods are considered. Small imbalances between inputs and outputs, resulting from some externally induced system change, can either cause reservoirs to build up or to become depleted with time. In addition, a change in one component may be expected to affect other components subsequently. For example, the current buildup of carbon dioxide in the atmosphere is expected to affect the amount ultimately incorporated into deep ocean water. A consequence of these cycles operating at various time scales is that once changes are set in motion, the response may persist for long periods even after the initiating perturbation is no longer active.

Some climate modeling results suggests that if CO₂ emissions were to be stabilized at current rates, atmospheric concentrations would continue to increase for at least two hundred years (IPCC, 1995). This is in large part due to the long time scale nature of the ocean-atmosphere cycle. Because the oceans are slow to take up carbon from the atmosphere, CO₂ has a relatively long residence time (greater than 100 years) in the climate system. If at some point in the future, CO₂ emissions are greatly reduced or completely eliminated, atmospheric concentrations may take several hundred years to decrease substantially because of the long time over which ocean CO₂ is re-released into the atmosphere.

The response of climate systems to perturbations such as greenhouse gas concentration changes may be further complicated because of the apparent stochastic nature of climate. It is possible that climate may exhibit intransitive

behavior by settling into any of a series of difficult-to-predict alternate stable configurations. In turn, it could also be expected to show almost intransitive behavior by flipping between a limited number of alternate states in response to a perturbation (Goodess et al., 1992).

Figure 2.1 shows that the atmospheric carbon reservoir is increasing by about 3 billion tonnes per year. Although the impression is that this is due to fossil fuel combustion at about 5.6 billion tonnes per year, with the difference being incorporated into the oceanic reservoir, it is recognized that there remains some uncertainty regarding the magnitude of a number of the carbon fluxes. Whereas the potential role of clathrates is also uncertain, MacDonald (1990) concluded that methane release from clathrates is not significant at present. More recently, a number of researchers have concluded that part of this uncertainty ought to be attributed to terrestrial sinks. Gifford (1994) concluded that there was no credible hypothesis formulated to suggest that the oceans were providing a physio-chemical sink greater than (2.1 ± 1.4) billion tonnes of carbon per year. Various atmospheric modeling studies (e.g., Tans et al. 1989, Tans et al. 1990, and Ciais et al. 1995) have implicated a fairly significant terrestrial sink in the mid to northern latitudes of the Northern Hemisphere. Table 2.1 shows a summary estimate of the average annual carbon fluxes into the atmosphere and the subsequent fate of this carbon into various reservoirs for the decade 1980 through 1989. The quantities in Table 2.1 appear with respective estimated 90% confidence intervals.

In comparison to the quantities of carbon in storage, these annual fluxes are relatively small. They are significant however, because over a period of centuries,

the magnitude of some reservoirs can change significantly if the fluxes continue. All this suggests that the human practices that emit greenhouse gases to the atmosphere may be expected to affect climate not only in the short term but also in the long term, and possibly in ways which are difficult to predict⁷.

Table 2.1: Summary Estimate of Carbon Fluxes for the Decade 1980 through 1989 (billions of tonnes of carbon per year).

CO ₂ Sources	
Fossil fuel combustion and cement production	5.5 ± 0.5
Tropical deforestation and other land use changes (net)	1.6 ± 1.0
Total	7.1 ± 1.1
Partitioning among reservoirs (sinks)	
Storage in atmosphere	3.2 ± 0.2
Oceanic uptake	2.0 ± 0.8
Uptake by Northern Hemisphere forest growth	0.5 ± 0.5
Additional uncharacterized terrestrial sinks	1.4 ± 1.5
Total	7.1 ± 1.1

Source: Schimel et al., 1994.

There are also a number of human-made or industrial-origin chemicals that are important greenhouse gases. These include chlorofluorocarbons (CFCs) and their substitutes, hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs) and sulphur hexafluoride. Although the emissions of these gases are relatively small in quantitative terms, they are significant because they have

⁷ The IPCC report "Climate Change 1995" provides a good review of predictions of future CO₂ concentrations and fluxes.

a much greater global warming potential (GWP) compared to carbon dioxide. The GWP of a greenhouse gas is a measure of its ability to trap infrared radiation. It takes into account the different molecular radiation absorption abilities (i.e., the radiative forcing capacity) of the various gases as well as the longevity of the respective gas in the atmosphere. The IPCC recommends that a time horizon of 100 years be used to standardize the GWP of greenhouse gases (Environment Canada, 1997). Like carbon dioxide, these other greenhouse gases are involved in global cycles with various reservoirs and active flux processes.

The FCCC requires annual reporting of inventories of anthropogenic emissions of all greenhouse gases not controlled by the Montreal Protocol⁸. The GWP of these greenhouse gases are shown in Table 2.2 for three different time horizons. With these GWP values, it is possible to express the quantitative emission of all greenhouse gases in carbon dioxide equivalent units. For example, over a 100-year time horizon, methane is 21 times as effective at trapping heat in the atmosphere as carbon dioxide. This means that the quantitative emission rate of methane can be multiplied by 21 to specify the CO₂ equivalent emission. Table 2.2 shows that some of the human-made greenhouse gases listed above are important – they have large GWP values – because they have long lifetimes in the atmosphere.

⁸ The Montreal Protocol is an international agreement established in 1988 for the purpose of eliminating the emission of anthropogenic ozone-depleting gases such as CFCs.

Table 2.2: Global Warming Potential (GWP) of Various Greenhouse Gases.

Gas	Chemical Formula	Lifetime (years)	GWP (Time Horizon in years)		
			20	100	500
Carbon dioxide	CO ₂	Variable	1	1	1
Methane	CH ₄	12 ± 3	56	21	6.5
Nitrous oxide	N ₂ O	120	280	310	170
HFC-23	CHF ₃	264	9,100	11,700	9,800
HFC-32	CH ₂ F ₂	5.6	2,100	650	200
HFC-125	C ₂ HF ₅	32.6	4,600	2,800	920
HFC-134a	CH ₂ FCF ₃	14.6	3,400	1,300	420
HFC-152a	C ₂ H ₄ F ₂	1.5	460	140	42
HFC-143a	C ₂ H ₃ F ₃	48.3	5,000	3,800	1,400
HFC-227ea	C ₃ HF ₇	36.5	4,300	2,900	9950
Sulphur hexafluoride	SF ₆	3,200	16,300	23,900	34,900
Perfluoromethane	CF ₄	50,000	4,400	6,500	10,000
Perfluoroethane	C ₂ F ₆	10,000	6,200	9,200	14,000

Source: IPCC, 1996.

2.3 EVIDENCE OF INCREASING LEVELS OF GREENHOUSE GASES

Since the start of the industrial era, various human activities have lead to significant changes in the composition of the atmosphere. Table 2.3 shows the presumed concentration changes of the three main greenhouse gases from the pre-industrial period to the present (1992). Current levels are determined from actual on-going atmospheric gas analysis and past levels are based on the analysis of gas concentrations in air bubbles trapped in polar ice sheets as they are built up by annual additions of snow. Other greenhouse gases such as perfluorocarbons, HFCs and sulphur hexafluoride were virtually non-existent in 1800 AD. Although current levels are measurable, their combined contribution to enhanced radiative forcing

compared to carbon dioxide, methane and nitrous oxide is quite small, less than 1.5% in Canada in 1995 (Environment Canada, 1997).

Table 2.3: Atmospheric Concentrations of Greenhouse Gases.

Gas	Pre-industrial Concentration	Concentration in 1992	Percent Increase
Carbon dioxide	278 ppmv	356 ppmv	28
Methane	700 ppbv	1714 ppbv	145
Nitrous oxide	275 ppbv	311 ppbv	14

Source: Prather et al., 1994.

ppmv = parts per million by volume.

ppbv = parts per billion by volume.

Continuous and precise atmospheric CO₂ concentrations have been measured since about 1958 at two monitoring locations – at Mauna Loa, Hawaii and at the South Pole, Antarctica. Figure 2.2 shows that CO₂ in the atmosphere at Mauna Loa has risen from about 315 ppmv in 1958 to about 364 ppmv in 1997 (Keeling and Whorf, 1998a).

The separate measurements at the South Pole and at Mauna Loa show a slight variance between the Southern and Northern Hemisphere CO₂ concentrations – about 3 ppmv higher at Mauna Loa in 1992 (Schimel et al., 1994). The Northern Hemisphere is a much larger source of CO₂ because of both greater population and a greater level of industrialization. The difference therefore reflects a time lag in atmospheric mixing between the hemispheres. Annual average CO₂ concentrations at Alert in the Canadian Arctic have been measured continuously since about 1975

Data from Keeling and Whorf (1998a).

and are generally found to be a few ppmv higher than those at Mauna Loa (Environment Canada, 1997a). That these inter-station differences are small compared to the overall increase in concentrations during the past 40 years suggests that atmospheric mixing on a global scale is relatively thorough at a time scale of just a few years. At Mauna Loa, seasonal variations of about 6 ppmv are also evident (Keeling and Whorf, 1998a) with a peak typically appearing in May, which is the end of the winter heating season in the northern hemisphere and the low occurring in September/October, which is the end of the northern growing season. In summary, the observed overall trend, the minor inter-hemisphere differences and the seasonal variations are all consistent with an anthropogenic origin for the increasing atmospheric CO₂ levels.

Atmospheric CO₂ concentrations based on ice core air bubble analysis from Antarctica. Cores DE08 and DSS are from Law Dome (Etheridge et al., 1998). Core Siple is from Siple Station (Neftel et al., 1994). South Pole is atmospheric measurements from Keeling and Whorf (1998).

Ice core data from Antarctica show CO₂ at around 280 ppmv for the period from about 1000 AD to 1800 AD and starting to rise exponentially after 1800 AD to the recently observed levels as discussed above (see Figure 2.3). Based on other analyses of Antarctic ice cores, current CO₂ concentrations appear to be higher today than any experienced during the past 200,000 years (Schimel et al., 1994).

Ice core gas analysis has also provided evidence that trends in atmospheric methane and nitrous oxide concentrations from pre-industrial times to the present are similar to that described for carbon dioxide (Prather et al., 1994). In addition, regular atmospheric analysis over the past 15 to 20 years shows directly that concentrations

of methane and nitrous oxide have continued to increase (Prather et al., 1994). Although methane and nitrous oxide additions to the atmosphere have both natural and anthropogenic sources, recent trends appear to be correlated to the increasing level of the various human activities which generate these gases. Consequently, the potential impact on enhanced radiative forcing attributed to methane and nitrous oxide is also of concern.

2.4 GREENHOUSE GAS SOURCES

Emissions of the three primary anthropogenic greenhouse gases may be quantified according to a number of different schemes. For example, emissions may be categorized according to the primary source such as fossil fuel combustion or agriculture or according to an economic-defined sector such as transportation or industry. The IPCC currently specifies that greenhouse gas emissions must be reported according to the six main categories listed below.

- Energy
- Industrial Processes
- Agriculture
- Land Use Changes & Forestry
- Waste
- Solvents and Other Products

Carbon dioxide, methane and nitrous oxide are all included in the greenhouse gas emissions from the energy category and comprise emissions from both the

stationary⁹ and mobile combustion of fossil fuels. Additional sources of these three greenhouse gases are listed below (data from Environment Canada, 1997).

Carbon dioxide	Methane	Nitrous oxide
<ul style="list-style-type: none"> • Cement and lime production • Limestone and soda ash consumption • Waste incineration • Agricultural soils • Other non-energy petroleum products 	<ul style="list-style-type: none"> • Landfills • Animals • Manure • Wastewater treatment • Composting • Waste incineration 	<ul style="list-style-type: none"> • Nitric and Adipic acid production • Fertilizer use • Propellants and anesthetics • Waste incineration • Wastewater treatment

Prior to the recent interest in climate change and greenhouse gas emissions, comprehensive greenhouse gas emission inventories were not computed. Globally, CO₂ emissions from energy sources comprise the vast majority of all greenhouse gas emissions. Reasonably reliable estimates of CO₂ emissions can be derived from historical statistical records of fossil fuel consumption and cement manufacture (Schimel et al., 1994). Figure 2.4 shows the trend in CO₂ emissions from fossil fuels, gas flaring and cement manufacture for the period 1850 through 1996 based on data by Marland et al. (1999). It indicates that the trend in these CO₂ emissions roughly parallels the rise in atmospheric CO₂ concentrations shown in Figure 2.3 for the same period, suggesting a direct cause and effect relationship. In fact, it has been concluded that the increase in carbon dioxide in the atmosphere is "almost entirely due to human activities" (Environment Canada, 1997).

⁹ This category includes a number of additional sources of greenhouse gas such as prescribed fires, wood and wood waste and pipeline losses.

Carbon emissions from fossil fuel combustion, cement manufacture and gas flaring. Data (preliminary) from Marland et al., 1999.

Figure 2.4 also indicates that worldwide, CO₂ from these sources in 1990 amounted to approximately 6.1 billion tonnes carbon or about 22.4 billion tonnes carbon dioxide. Data for 32 countries¹⁰ that are included in Annex I to the Convention (FCCC) shows that their total anthropogenic CO₂ emissions, excluding land use change and forestry for 1990 were 13.8×10^9 tonnes (FCCC, 1997). The FCCC (1997) report also indicates that 99.7% of these CO₂ emissions originate from the energy and industrial processes categories (97 % and 2.7% respectively). On this

¹⁰ Australia, Austria, Belgium, Bulgaria, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Spain, Switzerland, United Kingdom and United States. Greenhouse gas emission data for these are available in a consistent and comprehensive format.

basis, it is concluded that these 32 countries together contribute about 60% of the global CO₂ emissions. Figure 2.5 shows the relative share that the individual gases contributed to the

total greenhouse gas emission inventory for 1990 by the 32 Annex I parties.

It is not clear whether these proportions would be applicable to the sum of all global greenhouse gas emissions. Because the 32 countries likely represent the larger fraction of the earth's industrial activity, there may be various explanations that might lead to the conclusion that the above proportions would not hold for all countries. For example, developing countries are less likely to have significant nitric acid or adipic acid production. They may also be less likely to employ chemical fertilizers in their agriculture to the same extent as in industrialized countries. Consequently, developing countries may not have as great a proportion of nitrous oxide in their collective greenhouse gas emissions as shown above. Nevertheless, it is not expected that the various proportions on a global basis would be substantially different from the overall average of the 32 industrialized countries.

In Canada, CO₂ annual emissions from fossil fuel use more than doubled during the 20 year period from 1958 to 1978 (from 185 Megatonnes to 414 Megatonnes respectively). Since 1978 they have continued to increase, but at a slower pace, rising to 475 Megatonnes in 1994 (Environment Canada, 1996). For 1995, Canada's total greenhouse gas emissions were 619 Megatonnes CO₂ equivalent, or about 57.3 kilograms per person per day (Environment Canada, 1997)¹¹. The compositional makeup of the 1995 emissions and the relative distribution of the total inventory according to the approved IPCC categories are shown in Tables 2.4.

Table 2.4: Canadian Greenhouse Gas Emissions in 1995 by IPCC Category and by Component Gases.

IPCC Category	Percent of 1995 Emissions	
Energy	85.1	
Industrial processes	7.1	
Agriculture	4.4	
Waste	3.1	
Land use change and forestry	0.1	
Solvents & Other products use	0.2	
1995 Emissions		
Greenhouse Gas	kilotonnes CO ₂ equiv.	Percent
Carbon dioxide	500,000	80.8
Methane	78,000	12.6
Nitrous oxide	33,000	5.3
Perfluorocarbons	5,600	0.9
HFCs	500	0.1
Sulphur Hexafluoride	2,000	0.3
Total	619,100	100

Source: Environment Canada, 1997a.

¹¹ Environment Canada concludes that the uncertainties associated with these estimates are about 4% for carbon dioxide, 30% for methane and 40% for nitrous oxide.

These data show that Canada's emissions have a constituent gas makeup similar to that of the sum of the 32 Annex I parties indicated previously. One area where Canada's greenhouse gas emissions seem to be somewhat different from the aggregate of the 32 Annex I parties is in the fraction of CO₂ emitted from energy sources. As noted earlier, overall CO₂ emissions from energy sources account for about 97% of all anthropogenic CO₂ emissions for these parties. The FCCC (1997a) indicates substantial variability in the proportion of a country's CO₂ emissions from industrial processes. Canada's CO₂ emissions from industrial processes in 1990 were 4.7% of all CO₂ emission whereas compared to the US or to the aggregate, CO₂ emissions from industrial processes were 1.1% and 2.6% respectively. In addition, Canada reports a large quantity of CO₂ from "other" sources. In fact, for 1990 these accounted for about 85% of all parties' CO₂ emissions from other sources. The reasons for these dissimilarities are not obvious and will not be resolved here. However, the consequence is that for Canada, the percent of CO₂ emissions from energy sources for 1990 as reported in FCCC (1997a) was 93.7%.

A breakdown of all greenhouse gas emissions for Canada in 1995 by energy and non-energy sources is shown in Table 2.5 (Environment Canada, 1997). Although the IPCC has developed comprehensive procedures to document emissions of all greenhouse gases from a wide spectrum of sources, new sources of emissions and revisions to the methods for computing them continue to be developed. For example, under the latest procedure updates, Canada's greenhouse gas emissions for the years 1990 through 1995 have been revised. For 1995, the new figure is 652,000 kilotonnes CO₂ equivalent (Environment Canada, personal communication). However, since most published documents, including Environment Canada (1996)

and (1997) as well as FCCC (1997) and (1997a) have not yet been revised, the greenhouse gas emission data referenced in this section will be those as found in existing publications.

Table 2.5: Canadian Greenhouse Gas Emissions in 1995 (kilotonnes CO₂ Equivalent).

Gas	Energy Sources ¹²	Non-energy Sources
CO ₂	461,000	38,600
CH ₄	39,000	39,600
N ₂ O	17,000	16,100
Others	–	9,000
Total	517,000	102,300
	619,000	

Source: Environment Canada, 1997.

Canada's greenhouse gas emissions are very closely correlated to the level of the country's economic activity (Figure 2.6). This would appear to be a direct consequence of the fact that the majority of the emissions are derived from energy use. It also implies that it could require some radical solutions to substantially reduce greenhouse gas emissions – assuming that the probability of a new wonder-technology emerging in the short term is relatively low. It is considered unlikely that

¹² The sub-total of Energy Source emissions here is less than 0.851 times the total emissions as given earlier for the IPCC categories by 10,000 kilotonnes. This reason for this difference has not been resolved, but it appears to be an artifact of differences in the way Canada reported inventories before and after the most recent IPCC guidelines. For example, as shown differently in Environment Canada 1997 and Environment Canada 1997a.

Figure 2.6: Canadian CO₂ Emissions from Fossil Fuel Use vs. Gross Domestic Product.

Data from Environment Canada, 1996.

Change in slope corresponds to a slowing of CO₂ emissions growth following the oil-price shock period of the late 1970s.

the majority of Canadians would be in favor of reducing the country's GDP to accomplish the prescribed greenhouse gas reductions.

The relative contributions to the total energy source greenhouse gas emissions from selected sub-component sources are shown in Table 2.6. The transportation sector is clearly revealed as one of the major contributors to Canada's inventory of greenhouse gas emissions. Almost one third of the total energy source emissions, or about 27% of all greenhouse gas emissions for 1995, are derived from the use of fossil fuels for powering all the varied forms of transportation systems in this country. Furthermore, just over one half (56%) of the transportation sector greenhouses gas emissions, or about 15% of the national total, originates from gasoline-powered automobiles and light-duty gasoline trucks – a category that includes mini vans, pickup trucks and sport utility vehicles (Environment Canada, 1997a).

Table 2.6: Sector Contribution to Canada's Energy Source Greenhouse Gas Emissions (1995).

Sub-component of Energy Source	Contribution to total Energy greenhouse gas Emissions (% of 527 Megatonnes CO ₂ equiv.)
Energy & Energy Transformation Industries	31
Industrial Processes	14
Transportation	31
Commercial/Institutional	6
Residential	8
Oil/Natural Gas Systems	9
Coal Mining and others	1

Source: Environment Canada, 1997a

Canadians are very dependent of automotive transport. In 1995, combined ownership of automobiles and light-duty gasoline trucks was 15.58 million vehicles. These were driven approximately 335 billion kilometres and consumed approximately 32.5 billion litres of gasoline (Environment Canada, 1997a). On a crude aggregate basis, this equates to a greenhouse gas emission rate of about 265 grams CO₂ equivalent per kilometre traveled¹³.

Natural Resources Canada (1997) projected the number of automobiles and light duty truck to increase by about 8% and 46% respectively over 1995 levels by the year 2010. This does not bode well for national greenhouse gas emissions because, even with improvements in fuel efficiency, a shift away from automobiles, which tend to be more fuel-efficient, to light duty trucks implies greater levels of greenhouse gas emissions in the future. In addition, the average number of kilometres driven per year for cars was projected to increase marginally while light truck annual mileage was projected to remain relatively constant. In 1997, Environment Canada was still projecting transportation greenhouse gas emissions to continue to increase and to become a larger share of total emission between now and the year 2020 (Environment Canada, 1997).

Because it is such a large contributor to our greenhouse gas emissions, the transportation sector clearly ought to be considered as an essential area where emission reductions will have to be made. The preceding information would seem to indicate as well that this might not necessarily be accomplished by Canadians

¹³ These data refer to only the consumption of the fuel. They do not include emissions associated with manufacturing or maintaining vehicles or roads and highways, etc.

reducing the amount they drive. Alternate means of reducing emissions from the transportation sector will therefore be required if Canada is to meet its international commitments for greenhouse gas reductions. These will be discussed subsequently (Section 2.6.2).

2.5 RESPONDING TO GLOBAL CLIMATE CHANGE

2.5.1 EVIDENCE OF CLIMATE CHANGE

It has been said earlier that climate seems to have a natural tendency to change as a result of a variety of forcing and feedback factors. At issue in the current context is the detection of change, i.e., demonstrating that an observed change in climate is statistically significant within the range of short-term year-to-year climate variability. Instrument-based records of global temperatures are really only available since about 1860. Consequently, evidence of past climate changes must either be inferred from historical accounts and descriptions or based on scientific interpretation (e.g., geology, dendrochronology, palaeoecology and/or glaciology, etc.). A reconstruction of air temperatures in Antarctica during the past 220 thousand years based on analysis of the deuterium content of ice cores not only shows temperature variations by as much as 8°C (Jouzel et al., 1993), but that changing trends occur at different time periods (see Figure 2.7). Furthermore, the temperature changes seem to be very closely tied to changing carbon dioxide and methane concentrations. Such glacial-interglacial cycles clearly constitute changing global climates.

In the shorter term, evidence of changing climates can be deduced from the written historic record of civilization. For example, warmer temperatures during the

Figure 2.7: Temperature Anomalies and Methane and Carbon Dioxide Concentrations over the Past 220,000 Years as Derived from the Ice Core Record at Vostok, Antarctica.

Source: Jouzel et al., 1993.

medieval warming period can be inferred from the fact that there are preserved documents that indicate extensive wineries operating in Great Britain and significant Norse settlements flourishing on Greenland during the medieval warming epoch (Bryson and Murray, 1977). Later, during the “Little Ice Age”, substantial glacial advance in the Alps was observed and recorded because of a marked cooling of the climate in Europe (Bryson and Murray, 1977). Although this kind of recent historical climatic shift is usually described locally because extensive worldwide documentation usually does not exist, there is some evidence that they may have been global scale events. For example, the Little Ice Age seems to have been prevailing in South America, New Zealand and Antarctica in addition to Europe and North America (Goodess et al., 1992).

In the very recent past, since the extensive measurement of spatial and temporal global air temperatures with instruments, it has been possible to deduce that the global mean surface air temperature has increased by between 0.3 and 0.6 °C since the latter part of the 19th century (IPCC, 1996). In fact, it appears that the twentieth century global mean temperature will be at least as warm as any other century since at least 1400 AD (IPCC, 1995a). During the same period, the mean surface air temperature in Canada seems to have increased by about 1°C (IPCC, 1996 and Environment Canada, 1997a). The Environment Canada (1997a) data in Figure 2.8 indicate substantial year to year variability, but the overall trend does seem to be emerging to support the conclusion of increasing temperatures. Most recent climate modeling studies now simulate the observed warming trend quite well and show that it is not likely due to natural causes alone (IPCC, 1995a). Some predictions of future

Figure 2.8: Canadian Average Temperatures.

Data from Atmospheric Environment Service, Environment Canada.

Temperature change is the variation in respective temperatures from a reference mean value calculated for the period 1951 through 1980.

greenhouse gas concentrations and climate change, manifest primarily by rising temperatures, are discussed in the following section.

2.5.2 MITIGATION

The large quantities of greenhouse gases released to the atmosphere by human activity during the past 100 years – much of which now originate from the combustion of fossil fuel in transportation – have increased the concentrations of these gases to the point that significantly enhanced (positive) radiative forcing on a global scale may be expected. In the same period, average global air temperatures appear to have increased and it appears that a climatic change is underway.

However, because of the extreme complexity of the climate system, it is difficult to attribute a cause and effect relationship between human greenhouse gas emissions and climate change which can be used to predict with reasonable certainty how much change may be expected for a particular degree of atmospheric increase.

Nevertheless, the epistemic community has come to a consensus that mitigation – preventing the buildup of greenhouse gases in the atmosphere – is the most prudent and pressing course of action for this planet.

The IPCC (1995) distinguishes between two primary mitigation strategies:

- Limiting or reducing greenhouse gas emissions and
- Enhancing greenhouse gas sinks.

The most straightforward mitigation strategy would seem to be the reduction of greenhouse gas emissions at the source. In fact, the United Nations Framework Convention on Climate Change has adopted as its ultimate objective the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (IPCC, 1995, paragraph 1.4). It is further noted that a “safe” level is one that allows the following:

- Ecosystems would adapt naturally (it is unclear how this would be defined),
- Food production would not be threatened and
- Economic development continues to proceed in a sustainable fashion (IPCC, 1995).

An obvious challenge in this regard is defining what constitutes a safe level of greenhouse gas concentrations. One way of addressing the issue of climate change mitigation is to conceptualize the following basic sequence of events. First, it is considered necessary to stabilize or reduce greenhouse gas emissions. This may then be expected (eventually) to lead to a stabilization or reduction in greenhouse gas concentrations, which in turn may be expected to stabilize climate change. The following examination provides an assessment of current assumptions about the link between the level of climate change which may be expected as a consequence of particular levels of atmospheric loading of greenhouse gases.

In 1992, carbon dioxide contributed about 64% of the extra radiative forcing associated with increased concentrations of greenhouse gases in the atmosphere (IPCC, 1995a). This is expected to increase to about 75% by the year 2100 (IPCC,

1995). Carbon cycle models indicate that even if carbon dioxide emissions were maintained at their 1994 levels of about 7 billion tonnes (Gt) C, atmospheric concentrations would continue to increase for at least 200 years (IPCC, 1995). Further, these models show that the stabilization concentration is a function of the total anthropogenic loading expected over an extended period as in Figure 2.9. For example, at a total loading of 630 billion tonnes C over the period 1991 through 2100, the stabilized (future) atmospheric CO₂ concentration would be about 450 ppmv (IPCC, 1995).

In the preceding example, the total CO₂ loading equates to an average of 5.7 billion tonnes C per year, a value about 82% below 1994 levels. Various IPCC (1995) emission scenarios (IS92a through f) predict accumulated emissions from 1991 through 2100 ranging from 770 billion tonnes to 2190 billion tonnes carbon. Clearly, substantial reductions in emissions will be

required even to stabilize CO₂ concentrations at levels below 500 ppmv, or almost double the pre-industrial period concentration. At 500 ppmv, the extra radiative forcing from carbon dioxide will be about 3.5 Watts per square metre, or about 1.4 times the current total forcing from all greenhouse gases (IPCC, 1995b).

Figure 2.9: Stabilized CO₂ Concentration vs. Accumulated Anthropogenic Loading 1991 through 2100

Data derived from IPCC, 1995.

The degree of climate change expected as a result of anthropogenic greenhouse gas emissions remains somewhat speculative. It will also be governed by the level of aerosols, which tend to cause negative forcing, thereby counter-acting the greenhouse effect. Results of some modeling are shown in Figure 2.10 where the predicted equilibrium temperature increase from 1990 levels is plotted against selected stabilized CO_2 concentrations at 450, 650 and 1,000 ppmv respectively (IPCC, 1995). These predicted temperature increases are for CO_2 alone and do not include forcing resulting from other greenhouse gases, nor any change from accumulated emissions prior to 1990.

An other important issue in the context of increasing greenhouse gas concentrations is discerning how much the warming that might be expected for a given level of greenhouse gas increase will in turn cause “damage” to ecosystems, agriculture and economic systems. Although modeling of greenhouse gases and radiative forcing may give some specific predictions of

future global average temperatures with reasonable confidence (e.g., the mid-range IPCC emission scenario IS92a projects a global average temperature rise relative to 1990 of about 2°C by the year 2100), regional scale predictions and most other

associated impacts and effects are less clearly characterized. Nevertheless, recent refinements in climate modeling seem to be permitting better predictions at spatial scales less than global and temporal scales less than annual and predict effects such as the following (IPCC, 1995a):

- Greater surface warming of the land than of the sea in winter.
- Maximum surface warming in high northern latitudes.
- Little surface warming in the Arctic in winter.

Evidence of increasing correspondence between observed and model-predicted geographical, seasonal and vertical climate change patterns is also considered to be a key element in linking anthropogenic influences to climate change, i.e., demonstrating the cause and effect relationship. Other predicted changes are more often described in general terms. For example, some of the more significant frequently quoted potential impacts include 1) a sea level rise of 50 centimetres by 2100¹⁴ (IPCC, 1995) and 2) an enhanced global hydrological cycle. This latter impact is widely expected to affect the frequency, severity and distribution of extreme weather events such as droughts, floods and storms (IPCC 1995).

Given the general and still rather uncertain nature of predictions of greenhouse gas increases vs. temperature increases and climate changes¹⁵, the international community faces a significant challenge to identify what emission reduction target(s) ought to be established. On the one hand, there will be tremendous pressure for

¹⁴ This is over and above the 10 centimetre to 25 centimetre increase already recorded for the past 100 years.

¹⁵ For example, the IPCC (1995, paragraph 3.1) concludes, “ it is not yet possible to link particular impacts with specific atmospheric concentrations of greenhouse gases”.

maintaining and/or increasing the socio-economic conditions which contribute to greenhouse gas emissions and on the other, there remains uncertainty as to how much dangerous interference with the climate system is caused by a particular level of greenhouse gas stabilization. Nevertheless, whether based on actual predictions of climate change or on the basis of prudent caution, the UNFCCC has developed mitigation policies which stipulate greenhouse gas emission reduction targets such as outlined in the Kyoto Protocol of 1997¹⁶. For most industrialized countries, the Kyoto protocol specified that greenhouse gas emissions should be stabilized at levels close to their 1990 emissions by 2012¹⁷. For example, Canada's target was set at 6% below its 1990 levels. Because the Kyoto Protocol only applies to industrialized countries, it applies to about 60% of global greenhouse gas emissions. On this basis, and in light of the earlier discussion of projections for the future, it therefore seems to imply a scenario of continued increases in greenhouse gas concentrations. However, it is recognized that the Kyoto Protocol addresses only the next 10 to 15 year period. It may therefore be considered a beginning effort at stabilizing greenhouse gas emissions and hence atmospheric concentrations and climate change. Section 2.6 describes potential mitigation strategies aimed at reducing greenhouse gas emissions from the transportation sector.

¹⁶ It is interesting to note that in the readily available literature relating to the operation of the FCCC, that it was not possible to find specific information on the rationale for the emission reduction targets contained in the Kyoto Protocol. There appears to be no mention of how these targets would correspond to a particular CO₂ concentration stabilization or an acceptable or prescribed level of climate change.

¹⁷ From Figure 2.4, this would suggest that global emissions would be stabilized at approximately 6,000 Megatonnes carbon per year – assuming no further increases in developing countries.

2.5.3 IMPACTS ADAPTATION

Impacts adaptation may be regarded as the complement to the issue of climate change mitigation. In this context, the question of adaptation is important for a number of reasons. First, it is useful to be reminded that “quantitative projections of the impacts of climate change on any particular system at any particular location are difficult because regional-scale projections [of climate change] are uncertain” (IPCC, 1995, paragraph 3.4). Second, because efforts to mitigate greenhouse gas emissions on a global scale are relatively recent, there is considerable uncertainty at present over the ultimate extent, the time frame for implementation and the overall effectiveness of any proposed mitigation measures. For example, it will likely be at least several years subsequent to 2012 before the world will know whether the Kyoto Protocol is being successfully implemented. Lastly, as was evident in the previous section, even if carbon dioxide emissions are stabilized at approximately current levels, atmospheric concentrations are likely to continue to increase for a considerable duration. Humanity ought therefore to expect that climate change and its associated impacts will likely continue to become more pronounced during the opening decades of the twenty-first century. Consequently, the early identification and eventual implementation of appropriate adaptation strategies to cope with climate change and its related impacts must also be considered a prudent course of action for the human community worldwide.

Adaptation – the extent to which a system can adjust in response to a changing climatic condition – depends on two related characteristics of a system: sensitivity and vulnerability. Sensitivity is a measure of system response because of a changing

climatic variable, for example, photosynthesis responds to both increasing temperatures and concentrations of CO₂. Vulnerability is the degree to which a system is damaged or harmed by the changing climatic variable. Sensitivity, vulnerability and adaptation are all determined by both the extent of climate change (e.g., how many degrees warmer) and by the rate of change. Generally, systems that are more vulnerable are less likely to adapt. For example, developing countries may be more vulnerable and unable to adapt than developed countries to a particular climate change variable because of their less favorable economic circumstances. Adaptive measures may therefore be targeted to reducing vulnerability.

Environment Canada (1997) identifies three broad categories of adaptive measures as follows:

- Tactical actions or decisions taken by those immediately affected by the climate change. For example, people may choose to move away from low-lying flood-prone areas.
- Strategic actions or decisions taken at the system or sector level. For example, forest fires are expected to become more frequent/severe in some areas due to climate change. The forestry industry may therefore decide to adopt alternate forest harvesting procedures that can reduce the negative impact of forest fires on the long-term sustainability of forest resources.
- Policy level changes in socio-economic systems, lifestyles, behavior, etc., such as the institution of revised immunization and other public health protection programs to counter possible changes in the susceptibility of areas to particular diseases.

Adaptive measures may also be classified according to the following general framework for implementation (Environment Canada, 1997):

- Bear losses

- Share losses
- Prevent effects
- Change use
- Change location
- Education/awareness
- Research

There are also three important aspects of impacts adaptation that relate to impacts mitigation which may be summarized as follow.

- Adaptation must not be seen as a substitute for mitigation. Even with fully successful mitigation, climate changes are still likely to occur because of the long time scale response of the ocean-atmospheric system to the accumulation of greenhouse gases up to now.
- Adaptation will likely become more difficult the longer mitigation measures are delayed.
- Significant adaptive measures will require their own implementation periods, are likely to involve substantial cost and may not be transferable from one region to another. These factors will all determine the particular local approach to adaptation and likely to mitigation as well.

2.6 MITIGATION STRATEGIES

2.6.1 OVERVIEW

As stated in a previous section, the overall goal of the UNFCCC is the stabilization of greenhouse gas concentrations in the atmosphere. To this end, the primary focus is on reducing the emission of greenhouse gases. This section focuses on potential mitigation strategies in the transportation sector.

Greenhouse gas emissions in Canada in 1990 were 599 Megatonnes (Mt) CO₂ equivalent (Environment Canada, 1997)¹⁸. In order for Canada to meet its Kyoto commitments therefore, this means that by the year 2012, emissions would have to be brought back down to 563 Mt CO₂ equivalent. For the year 2000, emissions are projected to be 666 Mt CO₂ equivalent (Ian McGregor, personal communication)¹⁹. It is not likely that significant measures to significantly reduce greenhouse gas emissions will be instituted before the year 2000²⁰. Consequently, the net amount of emission reduction required to meet the Kyoto commitment is 103 Mt CO₂ equivalent below the expected year 2000 level. In the subsequent discussion of emission reduction potentials for various proposed strategies, the level of benefit can be determined by comparing the projected emission saving with the 103 Mt CO₂ equivalent reduction commitment. If for example, a particular strategy is expected to reduce emissions by 5 Mt CO₂ equivalent, then it will be contributing 4.85% of the total emission reduction required to meet the Kyoto commitment.

It must be recognized that a sector's relative contribution to total greenhouse gas emissions should not necessarily determine its potential contribution to emission reduction. For example, the transportation sector should not simply be expected to reduce its contribution by 6% of the 1990 level – it may not be possible. Conversely,

¹⁸ According to the most recent IPCC inventory procedures.

¹⁹ Other projections of future greenhouse gas emissions are based on the older inventory procedure and as such are no longer relevant. In addition, projections further into the future become increasingly uncertain because mitigation measures may be introduced at various times. A projection to year 2010 on current assumptions therefore has limited usefulness. It is considered preferable to refer to an emissions gap between year 2000 levels and the Kyoto Protocol target instead of a gap between projected future emissions and the Kyoto target.

²⁰ Canada's National Climate Change Secretariat has been tasked to facilitate the release of a National Climate Change Strategy by December 1999

there may be relatively easy-to-implement strategies that could reduce emissions to a greater extent. The National Climate Change Secretariat has a mandate to identify and quantify all possible emission reduction strategies in all sectors. Actual implementation can then be based on selecting strategies according to minimal barriers to implementation and maximum contribution to emission reduction. Although there may be considerable uncertainty, possibly even controversy, as to what degree of benefit may be realized from a particular proposed strategy, in the aggregate, it may be expected that proposed solutions will have a positive benefit. However, quantifying the exact level of benefit of any particular strategy at this point is not essential to the current analysis.

2.6.2 TRANSPORTATION AND FUEL PROSPECTS

Because of its substantial contribution to Canada's greenhouse gas emissions inventory, it can reasonably be expected that the transportation sector will be required to come up with some substantial prospects for reducing emissions. To this end, the following three basic categories of approaches or strategies have been defined (Transportation Table – National Climate Change Process, 1998).

- Technological improvements involving either vehicles, fuels and/or infrastructure.
- Transportation use changes such as mode, vehicle type and methods of operating and/or maintaining vehicles.
- Transportation demand management approaches such as measures aimed at reducing vehicle traffic.

Table 2.7 at the end of this section summarizes the strategies identified by the Transportation Table – National Climate Change Process (1998) for reducing greenhouse gases in each of the above categories. This Issue Table was mandated to provide specific options by May 1999 for the transportation component of Canada's National Climate Change Strategy. For this purpose, the Transportation Table was, among other things, to investigate the feasibility of potential options by considering issues such as their technical feasibility/availability, the presence and nature of potential technological, economic, consumer acceptance and/or other barriers to implementation, and the potential impacts and/or benefits to be expected. When the National Climate Change Strategy is eventually released, it may show additional possibilities and/or a re-defining of the categories of possibilities. Nevertheless, the listing in Table 2.7 is considered largely representative of the kinds of options that might be included in the national strategy. It is considered more likely that details concerning the potential options, e.g., the degree of greenhouse gas emission reduction to be expected for the various strategies, the time frame and costs of implementation, etc., may be substantially revised from what is shown in Table 2.7. In this respect, it is therefore important to bear in mind that the greenhouse gas reduction potentials shown in the table (where applicable) constitute a preliminary attempt to specify these values. In so doing, they provide an initial estimation for the possibilities in the transportation sector, especially in the context of comparing the various possibilities.

A number of specific strategies for greenhouse gas emission reductions in the transportation sector have also been proposed in a joint-effort publication by the David Suzuki Foundation and the Pembina Institute for Appropriate Development

(1998). These are cited as examples of solutions that are considered readily implementable. They are listed below along with respective estimated greenhouse gas emission reduction prospects. Other than the proposal for increasing taxes, it is evident that these Suzuki/Pembina solutions correspond to specific possibilities listed in Table 2.7.

- The federal government should implement improved and mandatory fuel economy standards for vehicles (cars and light trucks). Average fuel efficiencies of 5.0 L/100 km for cars and 7.0 L/100 km for light trucks are expected to reduce greenhouse gas emissions by 25.8 Megatonnes per year when fully implemented.
- The federal government should impose increases in gasoline and diesel taxes at 2 cents per litre for 1999 and a further 2 cents per litre in each of the years 2002, 2004, 2006 and 2008. Greenhouse gas savings are estimated to be 7.5 Megatonnes per year by the year 2010.
- Various actions should be taken to increase the use of alternative modes of transportation (e.g., more government funding of public transit systems, introduction of disincentives for single-passenger vehicular travel, etc.). Greenhouse gas savings are estimated to be 4.7 Megatonnes per year.
- Federal regulations should require a mandatory 5% renewable energy content (e.g., ethanol) in gasoline by the year 2010. This is expected to reduce greenhouse gas emissions by 3.1 Megatonnes per year.
- Stricter enforcement of speed limits. A reduction of speed limits by 5 kilometres per hour on all highways where the limit is currently 90 kilometres per hour or greater is expected to result in a 2.2 Megatonnes per year greenhouse gas reduction.

For many of the possibilities shown in Table 2.7 – and also for others that may end up in the final National Climate Change Strategy – there will likely be any number of continuing questions concerning the prospects for actually adopting them. It is not

considered feasible at this time to attempt to anticipate or to identify all such possible questions. However, it is expected that there will be certain pertinent questions concerning a particular possible option that may be considered appropriate for the scope of a master's degree research paper. For this paper, it was decided to focus on the potential of alternative fuels to contribute to greenhouse gas reductions, and in particular on the use of ethanol in this regard because it appears to be an option that could be implemented with minimal difficulty in the short term²¹. As a compositional component (up to 10% by volume) in motor fuel in Canada, ethanol has experienced a steadily increasing demand since about 1992 and is now readily available to a large proportion of the population (Clark and Stumborg, 1996). In addition, all new vehicles manufactured today (cars and light trucks) can utilize ethanol-blended fuels up to 10% with no performance or durability detriment. In this context, it is suspected that there could be a substantial increase in the demand for ethanol in the near future if it ends up being aggressively promoted as part of Canada's National Climate Change Strategy (e.g., to the extent that ethanol comprises 5% of all motor fuel sold for cars and light trucks). A possible question in this regard is whether sufficient ethanol can be produced to meet such a potentially blossoming demand. The following section of this thesis provides an overview of the potential for ethanol to contribute to Canada's greenhouse gas reduction goals.

²¹ References to time frames that are specific to the context of this analysis are understood to be to the 2008 to 2012 time frame written in the Kyoto Protocol.

Table 2.7: Summary of Possible Greenhouse Gas Emission Reduction Strategies in the Transportation Sector.

Category	Description	GHG Emission Reduction Potential ²²
Technology Improvements		
– Vehicles	Implementation of proven and advanced technology innovations possibly available in the 5 to 15-year time frame (e.g. direct injection engines, aerodynamic improvements, advanced tires, etc.).	In the aggregate, 25 to 44% fuel consumption reduction within 15 years.
	Long term (greater than 15 years) advanced technology prospects (e.g. electric vehicles, hydrogen fuel cell or hybrid-electric vehicles, etc.).	0 to 63% reduction in fuel consumption.
	Proven technology improvements (5 to 10 years) for heavy trucks (e.g., aerodynamic improvements, advanced tires, etc.).	9% reduction in fuel consumption.
	Advanced, long term (>15 years) technology improvements for heavy trucks (e.g., insulated engines or fuel cell engines).	Additional 9% reduction in fuel consumption ²³ .
	Long term (10 to 20 years) advanced technology improvements (e.g., fuel cells) for rail locomotives.	40% reduction in fuel consumption.
	Gas turbine or diesel-electric power systems for ships.	Not yet determined.
	Advanced (10 to 20) technology improvements in aircraft (e.g., improved jet engines, etc.).	40 to 50% reduction in fuel consumption.

²² These are preliminary estimates from the Foundation Paper on Climate Change (Transportation Table – National Climate Change Process, 1998).

²³ Heat recovery prospects for insulated engines would result in substantial greenhouse gas savings over and above that from efficiency improvements alone.

Category	Description	GHG Emission Reduction Potential ²²
- Fuels	Currently available alternate fuels (e.g., natural gas, propane or ethanol from corn).	20% reduction (propane and natural gas) and 35% reduction (ethanol from corn) in greenhouse gas emissions.
	Ethanol from biomass (10 to 20 year projected availability).	80% reduction in greenhouse gas emissions.
- Systems & Infrastructure	Advanced traffic management systems such as monitoring and control systems for vehicles and highways.	Not yet determined.
	Advanced pavement.	Not yet determined.
	Improvements to inter-modal (road to rail) transfer systems.	Not yet determined.
	Advanced air navigation and control systems.	17% reduction in greenhouse gas emissions.
Transportation Choice and Uses.		
- Optimal Modal Use	Doubling use of public transit.	1.6 Mt annual greenhouse gas reduction.
	Doubling of inter-city bus use.	0.5 Mt annual greenhouse gas reduction.
	Doubling of inter-city train use.	0.03 Mt annual greenhouse gas reduction.
	10% shift of freight from truck to rail.	1.1 Mt annual greenhouse gas reduction.
- Scrapping Older Vehicles		One-time 0.1 Mt greenhouse gas reduction for Ontario.
- Vehicle Speed	Reduce highway speed from 120 kilometres per hour to 90 kilometres per hour.	20% reduction in fuel consumption.

Table 2.7 Continued.

Category	Description	GHG Emission Reduction Potential ²²
Transportation Demand Management		
- Urban Planning	Changes to planning policies such as higher density mixed use development.	Not yet determined.
- Telecommunications	Telecommuting 20% of the time.	Not yet determined for regions as a whole.
- Parking Reforms	Parking management and policies to reduce vehicular traffic in urban core areas.	Not yet determined.
- Alternate Work Schedules	Staggered commuting could reduce duration and intensity of travel.	Not yet determined.
- Increased Passenger Loadings.	Ridesharing and carpooling reduce the number of vehicle trips.	Not yet determined.
- Road Pricing	Road tolls may be used to reduce peak travel or to encourage alternate modes of transport.	Not yet determined.

Source: Transportation Table – National Climate Change Process, 1998.

3 ETHANOL FUELS AND GLOBAL CLIMATE CHANGE

3.1 ETHANOL FUEL PRIMER

As noted in the previous section, the use of ethanol-blend fuels in vehicle transportation is one possible means of reducing greenhouse gas emissions. The potential benefit of ethanol-blend fuels is made on two related points. The first is that ethanol is a renewable fuel, produced by the fermentation of renewable agricultural products (e.g., sugar cane, grain, corn or ligno-cellulose). In essence, the carbon dioxide released into the atmosphere during the combustion of ethanol is derived from carbon dioxide absorbed from the atmosphere by plants through photosynthesis. Looking back at Figure 2.1 of the Carbon Cycle, it is evident that if the use of renewable fuels can replace fossil fuel use, it can eliminate a source of new carbon being transferred from the very long geological time scale cycle into the relatively short time scale atmosphere-ocean and atmosphere-land cycles. This will only be valid however, if a second and equally important point is also true. Specifically, when compared to producing conventional gasoline, the net carbon balance for ethanol must be positive. This means that the sum of all greenhouse gas emissions associated with the use of conventional fossil fuel in the full production cycle for ethanol must be less than those associated with the full production cycle of the equivalent energy content in the conventional fuel that the ethanol replaces. In practice, as long as the greenhouse gas emissions from the use of conventional fuel in the production of ethanol are less than those from the production of conventional fuel plus the greenhouse gases from the combustion of the conventional fuel, some net benefit will exist. The issue of determining the degree to which this occurs is discussed in Section 3.3.

Ethanol has been a potential automotive fuel since the advent of the internal combustion engine. It can be utilized either as a relatively pure ethanol or when blended with conventional petroleum gasoline²⁴. For the most part however, prevailing economic and/or sociological circumstances have largely limited its appeal as an alternative to conventional gasoline – a substantial gap existed between the cost of ethanol production relative to that of conventional gasoline. Since the 1970s however, there has been increasing interest in the use of ethanol and other renewable fuels as alternative automotive fuels in response to some important concerns. At that time, some countries (e.g., Brazil and the United States) started to respond to perceived shortages of crude oil supplies and to the desire to reduce national dependence on foreign petroleum-based products by substantially increasing their level of investment in developing an ethanol-for-fuel industry. In the 1980s and primarily in the US, concerns over air quality degradation attributed to automobile exhaust gave further positive attention to ethanol. Because of its oxygen content, ethanol contributes to improved exhaust quality by reducing carbon monoxide emission. In addition, because it also increases the octane rating of gasoline, using ethanol as an oxygenating agent means that the use of other hazardous fuel additives such as benzene can be reduced or eliminated. More recently, an ever-growing interest in ethanol as a renewable fuel is developing because it is being promoted as a means of reducing the anthropogenic greenhouse gas emissions that are linked to climate change. With all this interest, a number of things have happened to narrow

²⁴ At present in North America, ethanol-blend fuels are either minor component (10% or less) or major component (85% or greater) products because the former can be utilized in regular fuel combustion engines while the latter requires certain engine modifications. The designation of ethanol-blend fuels follows the convention of an upper case E followed by a number to denote the percent ethanol content. E85 therefore refers a fuel containing 85% ethanol. The remaining fraction is conventional gasoline added to denature the ethanol.

the cost gap to the point where ethanol is closer to being cost competitive with conventional gasoline. The factors that have made this possible are the following (Canadian Renewable Fuels Association, 1998):

- Major technological advances in the energy efficiency of the ethanol production process (feedstock and fuel production stages) have been realized.
- The average real corn price (in Canada at least) has been trending downward since 1950 and generally continues to trend downward.
- Governments have introduced excise tax exemptions for ethanol used in blended automotive fuels.

Cemcorp (1992) estimated that the best sale price of ethanol from a new hypothetical 100 million litre per year dry-mill corn ethanol plant in Ontario²⁵ would be 47.1 cents per litre. With federal and provincial excise and other tax credits totaling 23.2 cents per litre, the net revenue for ethanol fuel would be 23.9 cents per litre. This compared reasonably close to the prevalent 22 cents per litre “rack” price (or refinery-gate price) of gasoline. It assumes however, that specific credits are applied to the distillers dry grains byproduct and that maximum additional “partnering” opportunities are realized (e.g., a feedlot operation). Byproduct credits and partnering opportunities reduce the ethanol production cost in this example by 13.1 cents per litre and 1.5 cents per litre respectively (Cemcorp, 1992). The Canadian Renewable Fuels Association (CRFA, 1998) concluded that with the cost of ethanol production from grain and/or corn in the range of 35 cents per litre to 45 cents per litre (compared to 19 cents per litre to 24 cents per litre for petroleum

²⁵ Corn is the preferred crop for ethanol production in Eastern Canada. In Western Canada, wheat or barley are the preferred source crops.

gasoline), ethanol provides maximal economic value when it is used as an oxygenate up to a maximum compositional level of 10% (E10).

Further technology improvements in both the ethanol production process and in the cornfield are expected to result in still lower costs. In fact, E85 is already available in some corn-rich states in the US (Minnesota, Iowa and Illinois) and North American automobile manufactures have begun producing vehicles designed for E85 use²⁶.

Ethanol produced from cellulose is expected to have even lower costs such that the competitive position of E85 increases substantially. However, full-scale production of ethanol from cellulose has not yet been demonstrated. A number of technical and economic hurdles need to be overcome before this process is adapted to full scale ethanol-for-fuel plants. Cellulose-based ethanol is therefore not expected to be a significant factor in the ethanol-for-fuel industry in the short term and will therefore not be factored into the current analysis. Nevertheless, much interest is being devoted to this potential process because the anticipated lower feedstock production costs and a high-energy content by-product translate to greater greenhouse gas emission reductions relative to corn or grain source ethanol. In this context, Foody and Tolan (1997) propose that an environmentally sustainable ethanol fuels industry – one that is fully competitive with gasoline as a primary transportation fuel – would ultimately become one of Canada's largest industries.

For various reasons, fuel ethanol development in Canada has lagged behind that of the US. However, in the past 5 to 10 years it has picked up substantially. Because

²⁶ E85 vehicles have been in common use in Brazil for at least a decade.

of this delayed entry into the ethanol-for-fuel market, Canada has been able to benefit by being able to start out with the best available technologies, especially in corn-based processes. This not only favors the economic prospects for ethanol, but also the environmental benefit of reducing greenhouse gas emissions to very high level. As will become evident, the comparison of greenhouse gas emissions from ethanol fuels is dependent not only on the formulation, but also on the source of the ethanol, the method of production and a number of other factors.

3.2 CURRENT CONTEXT

The Canadian ethanol-for-fuel production capacity in 1998 and the additional capacity of new production facilities projected to be in place by the end of 2000 are summarized in Table 3.1. Although some of the capacity from some of the existing ethanol producers is currently used to satisfy other industrial demands, because it is a minority fraction, it is considered reasonable to assume that the full 234 million litre capacity could be made available for fuel demands with relatively little difficulty. Because the projected near term additional capacity is essentially being installed to supply ethanol-for-fuel demands (CRFA, personal communication) and because of uncertainty about the Metalore Resources Ltd. plant actually being constructed in the near term, it is concluded that the total capacity shown in Table 3.1 (600 million litres without Metalore Resources Ltd.) is a good estimate of the availability of ethanol for fuel by the end of 2000.

One of the newest large-volume producers is the highly advanced 150 million litre per year Commercial Alcohols Inc. ethanol-for-fuel plant in Chatham, Ontario. It

began production in 1997 and uses a dry-milling process technology that is capable of producing ethanol at a rate of 390 litres per tonne or 9.9 litres per bushel of corn (CAI, personal communication). At a corn yield of 7.3 tonnes per hectare (1996 data for all Ontario from Ontario Corn Producers Association, 1998), this equates to a land requirement of approximately 53 thousand hectares or about 7.5% of Ontario's corn crop for 1996.

Table 3.1: Capacity of Canadian Ethanol-for-Fuel Plants: 1998 – 2000.

Producer	Capacity (million litres per year)
Mohawk Oil Co. Ltd. – Minnedosa, MB	10
Pound-maker AgVentures Ltd. – Lanigan, SK	12
Commercial Alcohols Inc. (CAI) – Tiverton, ON	23
Commercial Alcohols Inc. – Chatham, ON	150
Agri-partners International – Red Deer, AB	22
Tembec – Témiscaming, Quebec	17
Sub-total current production capacity:	234
Projected near-term additional capacity:	
CAI – Chatham, ON (expansion of existing plant in 1999)	150
Seaway Valley Farmers' Energy Cooperative Inc. – Cornwall, ON ²⁷	66
CAI/Quebec Grain Producers – Montreal, Quebec ²⁸	150
Metalore Resources Ltd. (MRL) – Alberta (in planning stage)	80
Total current and near-term fuel ethanol capacity (not including MRL)	600

Source: Canadian Renewable Fuels Association, personal communication.

²⁷ Expected to be in production in 1999.

²⁸ Planned for construction in 1999.

Canadian gasoline consumption by automobiles and light trucks in 1995 was 32.5 billion litres (Environment Canada (1997a). At the same time, ethanol consumption for transportation fuel was approximately 50 million litres or about 0.15% by volume²⁹. Gasoline consumption is expected to increase by 2.4% by the year 2000 (Natural Resources Canada, 1997). For automobiles and light trucks therefore, it is projected to be approximately 33.3 billion litres. If the total ethanol production capacity shown in Table 3.1 (600 million litres) is realized by the end of 2000 and fully made available for fuel, the proportion of ethanol to conventional gasoline will have increased by a factor of 12 to approximately 1.8% by volume in five years. This assumes that there is no net import of ethanol for fuel from the US.

In the context of the various transportation technology options presented in Section 2.6.2, the enhanced use of ethanol-blend fuels may be considered a relatively easy solution. Today's automobiles and light trucks can use E10 fuel as is – all North American automobile manufacturers now either approve or recommend the use of ethanol-blend fuel. E10 is also readily available. Up until recently, most ethanol-blended fuel in Canada has been sold by independent distributors as a specialty product that has been advertised as an environmentally beneficial product. In 1998, Sunoco began retailing gasoline in Ontario containing ethanol. However, it is not sold or advertised it as a unique product – it is simply an ingredient in the normal range of Sunoco's gasoline blends. Expanding the market for ethanol fuels might therefore be simply realized as a consequence of promoting greater consumer awareness and acceptability. At present however, there is not yet any proposed

²⁹ Natural Resources Canada (1997) reports ethanol use in 1995 to be 1 PetaJoule (10^{15} J). Ethanol has an energy density of 21.16 million Joules per litre.

national consensus or strategy to specify the contribution ethanol is expected to make towards reducing greenhouse gas emissions.

3.3 THE POTENTIAL FOR ETHANOL FUEL

The extent to which ethanol and ethanol-blend fuels can reduce greenhouse gas emissions is typically determined on the basis of a “total fuel cycle” analysis. This is a variant of the environmental assessment methodology commonly referred to as Life Cycle Assessment (LCA). LCA is an analytical approach used to understand and minimize the environmental impacts or burden of products, technologies, materials, processes, industrial systems, activities or services (Fava, 1994). The identifying element of LCA is that it evaluates the respective effects on the environment in a “cradle-to-grave” context. This is to ensure that over the entire life cycle of alternative products, a new product such as an alternative automotive fuel does not create a greater environmental concern than that caused by the production and use of the product to be replaced, in this case regular gasoline. Conversely, LCA is a suitable methodology to verify whether a new product with claims of environmental benefits is in fact superior to existing products in all respects.

Total fuel cycle analyses for alternative transportation fuels have been carried out by various researchers in the US for a number of years (e.g., Delucchi, 1997, Shapouri et al, 1995, Wang, 1996 and Wang et al., 1997). Wang (1996) provides a good review of other relevant and earlier fuel cycle modeling studies. It is neither practical nor essential to this thesis to describe the design of fuel cycle models or to conduct a comprehensive review of the results of their use. Because such models continue to

be refined on an on-going basis – both in terms of identifying applicable component processes and in terms of specifying various process parameter values – and because scenarios for analysis are multitudinous, any particular output can only be considered valid within a specified set of circumstances that may not have much longevity or that may not be applicable from one place to another. However, there does appear to be a recent convergence in the output of various models as long as they are comparing similar products in similar production/use circumstances. The current consensus seems to be that the net carbon balance for corn-based ethanol is clearly positive. In other words, the use of ethanol instead of conventional gasoline can be expected to contribute to the reduction of the greenhouse gas emissions.

The total fuel cycle model developed by Michael Wang at Argonne National Laboratories in Chicago, IL seems to be most often referenced in the context of the greenhouse gas emission reduction potential of corn-based ethanol for transportation fuels. This model demonstrated that the total fuel cycle greenhouse gas emissions anticipated for a 2000 model year car in 2005 using ethanol from corn (E100) would be 145 grams CO₂ equivalent per kilometre traveled compared to 213 grams CO₂ equivalent per kilometre traveled when using normal gasoline (Wang, 1996). This difference is 68 grams CO₂ equivalent per kilometre traveled and represents a 32% reduction in greenhouse gas emissions with the use of ethanol. A later use of the Wang model, which focussed on four mid-western states with high corn production rates, concluded that the greenhouse gas reduction benefit of using ethanol ranges from 36% to 39% on a distance traveled basis when the ethanol is blended into E10 and E85 respectively for use in selected 1997 model year cars and from 43% to 46% for vehicles in 2005 (Wang et al., 1997). This latter set of results seems to be widely

referenced in the Canadian context of promoting ethanol from corn as an alternative to conventional gasoline (e.g., various CRFA publications on the Internet). The CRFA (1998a) further concludes that in the case of corn grown in southwestern Ontario, the benefit could be up to 60%. The greater benefit is partly attributed to the high efficiency of the new CAI plant in Chatham and partly because other farm-related differences associated with growing corn in Ontario reduce the energy requirement for corn production (CRFA, 1998a).

The greenhouse gas reduction benefit of an ethanol-blended fuel can be calculated by multiplying the greenhouse gas benefit of ethanol (as in the above examples) by the fraction of the energy provided by the ethanol in the blend. This fraction is determined by the equation:

$$\text{Blend ethanol-energy fraction} = \frac{21.16F_E}{34.66F_G + 21.16F_E}$$

where F_E and F_G are the volumetric fractions of ethanol and conventional gasoline respectively, in the blend. The numeric constants are the energy density values for ethanol and conventional gasoline respectively in MegaJoules per litre. For E10 therefore, the blend ethanol-energy fraction is 0.064. With the above level of benefit estimates for ethanol from corn (e.g., 32% to 60% greenhouse gas reductions on an energy equivalent basis), the greenhouse gas reduction benefit of E10 relative to gasoline could therefore be in the 2% to 3.8% range per kilometre traveled (0.064×0.32 to 0.064×0.6).

Total fuel cycle greenhouse gas emissions associated with the use of regular gasoline are approximately 3 kilograms per litre (Pembina Institute, 1998). Greenhouse gas reductions using E10 would therefore be 60 grams to 114 grams CO₂ equivalent per litre of gasoline displaced. For the projected fuel consumption rate in 2010 (36.9 billion litres as in Section 3.2), the total annual greenhouse gas reduction achievable with a complete switch-over to E10 (in all automobiles and light trucks in Canada) could therefore be in the order of 2.2 Mt to 4.2 Mt. This is also approximately 2% to 4% of the gap between the anticipated emissions levels in 2000 and Canada's Kyoto Protocol emission reduction target (see Section 2.6.1).

The greenhouse gas emission reduction benefit per litre of ethanol may be determined as follows:

$$GHG_{\text{ethanol-volume}} = GHG_{\text{ethanol-energy}} \times GHG_{\text{gasoline-volume}} \times \frac{21.16}{34.66}$$

where $GHG_{\text{ethanol-volume}}$ is the relative ethanol benefit on a volume basis,

$GHG_{\text{ethanol-energy}}$ is the relative ethanol benefit on an energy basis and

$GHG_{\text{gasoline-volume}}$ is the greenhouse gas emission rate for gasoline (3,000 grams CO₂ equivalent per litre). The range of benefits given earlier for ethanol (32% to 60% on an energy equivalent basis) therefore equate to greenhouse gas emission reductions of 586 grams to 1099 grams CO₂ equivalent per litre of ethanol.

There also seems to be a professional consensus that the energy efficiency for producing ethanol from corn will continue to increase as the fuel ethanol industry becomes increasingly established. In addition, it is also expected that at some point

other biomass-based ethanol will become an important process and supply.

Consequently, it may be expected that the greenhouse gas benefits of ethanol could become more significant as well. In this context, the case study described and carried out herein is considered timely and particularly relevant to Canada's national strategy for reducing greenhouse gas emissions in accordance with commitments outlined in the Kyoto Protocol of 1997.

4 OVERVIEW OF EASTERN ONTARIO

4.1 GEOPHYSICAL ENVIRONMENT

The geographic region referred to in this thesis as Eastern Ontario is consistent with the Ontario Ministry of Agriculture, Food and Rural Affairs definition of the region (OMAFRA, 1995). It consists of the seven eastern-most counties and one regional municipality in Ontario and extends from about 44° to 46.3° north latitude and from about 74.4° to 78.4° west longitude. The roughly triangular-shaped area – largely bounded on the south by the St. Lawrence River and on the northeast by the Ottawa River – encompasses some 28,720 square kilometres of land and inland waterways.

As illustrated in Figure 4.1, Eastern Ontario includes territory within three primary and distinct geological zones (Johnson et al., 1992; Wilson, 1956). The southeast portion of the region is dominated by the Central St. Lawrence Platform and is characterized by Paleozoic bedrock formations variously overlain by glacial or lacustrine deposits. The geology of the northwest portion is markedly different, consisting predominantly of terrain on the Precambrian Shield where surface soils are generally formed on coarse stony till and/or with bedrock very close to the surface. A small area in the southwest of the Eastern Ontario region makes up part of the Western St. Lawrence Platform where bedrock formations and surficial deposits are generally similar to those in the southeast portion.

As will become evident in Section 4.3, this dominating physiographic distinction between the two major sections of Eastern Ontario (i.e., the southeast and northwest

Figure 4.1: The Eastern Ontario Region - Location and Geology.

Based on: Geological Map of Canada, Wheeler et al. (1997).

sections) is roughly paralleled by, and is likely the underlying reason for, observed differences in recent agricultural production trends between the group of counties predominantly in the southeast section and those predominantly in the northwest section. On this basis, it was decided that it would be appropriate to subdivide Eastern Ontario into at least two distinct agricultural production sub-regions. Since the smallest spatially contiguous entity that can be identified from the available agriculture-related data (e.g., LEG, 1984; OMAFRA, 1996, etc.) is the regional municipality or the county, each of these political sub-units can be assigned to either the southeastern or northwestern sub-region based on the “50% rule”. In order to avoid ambiguity and to ensure ease of reading in the ensuing discussion, it was decided to refer to the southeastern sub-region as the **OSL Region** (Ottawa - St. Lawrence Lowland) and to refer to the northwestern sub-region as the **CAS Region** (Canadian Shield). For the purpose of this analysis, the small section of Eastern Ontario which is in the Western St. Lawrence Platform (i.e., the extreme southwest corner of the region) will be included with the northwestern section with which it is contiguous. The rationale for the assignment and the listing of the counties to either the OSL or the CAS sub-region is shown in Table 4.1 below.

Overall, the OSL sub-region is characterized by a generally level to gently undulating to moderately undulating or rolling topography (Hoffman et al., 1964). Surface elevations range from about 47 metres above sea level at Lake St. Francis in the extreme east of the region to just less than 200 metres above sea level along the northwest margin of the Central St. Lawrence Platform. The soils of the OSL Region, not including the western portion of Leeds and Grenville, can be broadly lumped (by the author) into five main groups as shown in Table 4.2. It is estimated

that these groups account for at least 95% of the soils of the area as defined by Hoffman et al. (1964).

Table 4.1: Assignment of Counties to Sub-regions in Eastern Ontario.

County or Regional Municipality	Approximate % in:		Assigned to Sub-region ³⁰	
	Ottawa-St. Lawrence Lowlands (OSL)	Canadian Shield (CAS)	OSL	CAS
Prescott and Russell	100	0	✓	
Stormont, Dundas and Glengarry	100	0	✓	
Ottawa-Carleton (RM)	>90	<10	✓	
Leeds and Grenville	~70	~30	✓	
Lanark	~40	~60		✓
Frontenac	~20	~80		✓
Lennox and Addington	~25	~75		✓
Renfrew	<10	>90		✓

Table 4.2: Main Soil Groups for OSL Region of Eastern Ontario.

Group	Texture	Origin	Drainage	Stoniness
1	coarse	sand/gravel	good to imperfect	stone-free
2	medium	till	good	moderately to very stony
3	fine	till or lacustrine sediments	poor to imperfect	stone-free to slightly stony
4	very fine	till or lacustrine sediments	poor to imperfect	stone-free
5	medium	till, bedrock < 0.3 m	variable	moderately stony

Source: (Hoffman et al., 1964).

³⁰ Sub-region assignment based on +50% rule.

In the CAS Region, the topography is more variable, ranging from level to undulating to hilly, with a greater preponderance of hilly terrain (Hoffman et al., 1964).

Elevations range from about 74 metres above sea level at Lake Ontario in the southwest of the region to about 500 metres above sea level in large parts of western Renfrew County. The large majority (about 70% or greater) of soils in the CAS Region and in the western portion of Leeds and Grenville are medium to coarse textured, derived from till, coarse stony till and/or with bedrock at less than 0.3 metres from the surface. These soils are generally well drained and moderately to excessively stony (Hoffman et al., 1964). The remaining smaller fraction of the soils in the CAS Region consists variously of the kinds occurring in the majority of the OSL Region – especially in the southwest parts of Lennox & Addington and Frontenac³¹.

According to the Thornthwaite climate classification scheme, Eastern Ontario is entirely within the **BC'rc** climate zone (Gates, 1972). This is described as a humid climate with warm summers and cold winters, with even precipitation all year and with a 50% – 69% temperature accrual in summer. The prevailing climate throughout the region is reasonably uniform, with only minimal zonal variation.

Average summer (July) temperatures range from 20 °C to 25 °C, except in the most northwesterly portion where they are slightly cooler, ranging from 15 °C to 20 °C.

³¹ Although the majority of crop production in Lennox & Addington and Frontenac likely takes place on the southern, Western St. Lawrence Platform terrain, the overall landscape of the CAS Region is more complex than that in the OSL Region. This complexity is also expected to be a factor contributing to differences in crop production practices and patterns observed between the two groups of counties.

Mean winter (January) temperatures range from -10 °C to -12.5 °C through most of the region and from -7.5 °C to -10 °C in the extreme southwest and along the St. Lawrence River³². Annual accumulated Corn Heat Units (CHUs) are typically in the 2400 to 2700 range across the region (Land Evaluation Group, 1984). The mean annual precipitation level for the region is in the 800 millimetre to 1,200 millimetre range with roughly equal amounts received each month throughout the year. Some low-level intra-regional climatic variation exists. For example, temperatures in the southwest are somewhat moderated due to the proximity of Lake Ontario and the northwestern highlands generally receive slightly lower levels of precipitation (National Atlas of Canada, 1985).

All of Eastern Ontario is situated within the Great Lakes-St. Lawrence forest region of Canada (Environment Canada, 1991). Although much of the OSL Region has been cleared for agriculture and other uses, large parts of the CAS Region remain under forest cover. The region encompasses land in two terrestrial eco-zones. The Mixed Wood Plains eco-zone includes most of the OSL Region and parts of CAS Region. Here the soils are typically luvisols that support mixed deciduous-coniferous forests in a cool to mild, moist climate. In the Boreal Shield terrestrial eco-zone, which includes northern parts of the CAS Region, the soils are typically podzols and brunisols³³. A cold, moist climate supports coniferous and mixed coniferous-deciduous forest (Environment Canada, 1991).

³² Climatic data are for the period 1941 through 1970 as reported in the National Atlas of Canada (1985).

³³ These are very broad generalizations. Substantial variability in soil class exists throughout the region (National Atlas of Canada, 1985).

4.2 LAND RESOURCES FOR AGRICULTURAL PRODUCTION

In the early 1980s, the Land Evaluation Group (LEG) at the University of Guelph developed a land classification system to estimate the amount of land that is cleared and available for agriculture in Eastern Ontario (LEG, 1984). The LEG system defines and quantifies the available land resources according to seven land types (A through G) that have different biophysical properties relevant to the production of crops – primarily soil quality and soil moisture holding capacity. It is based on the Canada Land Inventory (CLI) rating system for agricultural capability (Canada Lands Directorate, 1965). The CLI rates land from a somewhat general crop management perspective – one that does not relate directly to crop yields. The LEG therefore re-organized CLI classes/sub-classes into the seven land type aggregations based on soil qualities relevant to crop productivity (LEG, 1984). The resultant LEG scheme therefore facilitates a more specific correspondence with yield expectations for major field crops. Table 4.3 shows the CLI classes/sub-classes comprising the seven land types (not soil types) and defines the CLI capability classes and limitation sub-classes.

The designation “cleared land available for agriculture” includes all land outside built up areas that may be utilized for crops and/or for pasture. According to this classification, there are some 922 thousand hectares of land cleared and available for agriculture in Eastern Ontario as indicated in Table 4.4. A detailed discussion of the procedures and sources of data used to enumerate the relative availability of the different land types for Eastern Ontario and the rationale for estimating respective crop productivity values can be found in LEG (1984). Estimated productivity values for major field crops on the different land types are presented in Section 5.3.4.

Table 4.3: Overview of the Land Classification System.

LEG Land Type	CLI Classes and Sub-classes Included
A	1, 2D, 2F, 2M, 2T & 3F
B	3D, 4D & 5D
C	3M, 3P, 3R, 4M, 3P, 4R & 5M
D	2W & 3W
E	4W & 5W
F	5P, 5R, 5T, 6P, 6R & 6T
G	3T & 4T
CLI Soil Class	Basic Soil Capability for Agriculture
1	No significant limitations for the production of common field crops.
2	Moderate limitations for common field crops.
3	Moderately severe limitations for common field crops.
4	Suitable for perennial forage crops but marginal for common field crops.
5	Suitable for perennial forage crops.
6	Suitable for perennial forages as pasture.
7	No agricultural capability.
8	Unclassified (built-up areas).
0	Organic soils.
Sub-class	Reason for Limitation
D	Undesirable soil structure and/or low permeability.
F	Low fertility correctable by careful management and fertilizer use.
M	Moisture limitation, usually due to soil's low water-holding capacity.
P	Stoniness.
R	Consolidated bedrock near surface.
S	Adverse soil characteristics in general.
T	Topography.
W	Excess water.

Source: Land Evaluation Group, 1984.

Table 4.4: Availability of Land for Agriculture in Eastern Ontario.

County or Regional Municipality ³⁴	Cleared Land Available for Agriculture (1,000's of hectares)							
	Land Type							Sum
	A	B	C	D	E	F	G	
Frontenac	13	5	7	1	10	19	2	57
Lanark	12	4	9	2	8	23	<1	60
Leeds & Grenville	26	6	16	2	37	57	<1	146
Lennox & Addington	8	2	7	1	28	33	<1	79
Ottawa-Carleton	32	15	24	17	29	27	0	144
Prescott & Russell	16	16	22	5	64	2	0	128
Renfrew	27	22	35	3	6	13	1	107
Stormont, Dundas & Glengarry	40	13	51	14	73	10	0	201
Eastern Ontario ³⁵	177	81	173	45	257	185	3	922

Source: Land Evaluation Group, 1984.

Land type F is suitable only for pasture (LEG, 1984). There are therefore 737 thousand hectares of land available for crops in Eastern Ontario. Not including land type F, the four eastern counties of Eastern Ontario include 70% of the total acreage available for crops while they comprise only 40% of the total land area. This is no doubt related to the physiographic distinction between the predominantly shield terrain of the CAS Region and the predominantly lowland terrain of the OSL Region as described in the previous section.

The LEG (1984) also concluded that there was extra production capacity for crops within the agricultural land base of Eastern Ontario. Specifically, their analysis of the production possibilities of Ontario agriculture showed that it would be technically

³⁴ Counties and Regional Municipalities are named as they exist today (1998).

³⁵ Totals may not add properly because of rounding in the source data set.

feasible to increase the production of four major crops (grain corn, soybeans, winter wheat, and oats/barley) by 1.45 times the respective actual production levels reported for the early 1980s.

4.3 AGRICULTURAL LAND USE

Recent agricultural land use data from the every five-year census surveys conducted by Statistics Canada were analyzed to provide a general summary of the nature of the agricultural economy of Eastern Ontario. Particularly, selected data on the amounts of various categories of land and specific land uses reported for the 25-year period between 1971 and 1996 were extracted from the census records to investigate whether there are any intra-regional differences in the kinds and amounts of agricultural activities practiced in the region.

Although there have been some changes in the way agricultural lands have been classified with successive surveys, particularly prior to 1986, Figure 4.2 shows that the trends in the reported acreage for four main categories of farm land have remained relatively steady during the decade 1986 through 1996. Most significantly, the amount of cropland seems to have remained relatively stable over the entire 25-year period at about 500 thousand hectares³⁶. Figures A.1 through A.4 in Appendix A indicate that the trends in the different land categories (total land, improved land,

³⁶ Statistics Canada (1996) reports that by following various control protocols, the Census of Agriculture data are expected to have "consistently high quality". Consequently, and because Statistics Canada's focus in data collection/reporting is at the county level, there are no data quality issues expected to detract from the validity of using these data in this research.

cropland and unimproved land) as reported for census farms on a county by county basis are all largely similar to those of the Eastern Ontario region as a whole. Going solely on this basis, there appears to be little rationale to conduct the subsequent land use analysis on an individual county basis instead of on an overall regional basis.

Figure 4.3 of the amount of cropland reported for 1996 by county and as a percentage of total county land shows that for both these designations, the four western counties (i.e., those in the CAS Region) have the smallest amounts. This is the first broad indication of an agricultural disparity between the two sub-regions of Eastern Ontario.

Figure 4.3: Cropland by County and as a Percentage of Total Land Area (1996).

Source: Statistics Canada - Catalogue No. 95-177-XPB.

The land areas seeded to a number of major crops, as determined from Statistics Canada census data for 1981 through 1996, are shown in Table 4.5 and Figure 4.4. The major crops of grain corn, fodder corn, soybeans, oats, hay and grains, which is the sum of winter wheat, barley and mixed grains, constitute the main land use of the land classified as cropland (see last row of Table 4.5). The average usage of land during the period 1981 through 1996 for these crops was about 480 thousand hectares, roughly 95% of the reported acreage of cropland. Major trends in these crops during this period are evident in Figure 4.4. Grain corn has been steadily increasing. Soybeans have also been substantially increasing. Hay has remained more or less steady. Grains and fodder corn have been decreasing while the sum of fodder corn and grain corn has been more or less consistent. These trends will be used as the basis for developing some of the constraints for the land use model described in Section 5.

An evaluation of county by county performance for these major crops shows that trends in crop production, based on acreage planted between 1981 and 1996, are variable by crop and by county. In order to evaluate the spatial consistency of crop production trends, the rank order of each county for each crop was determined. The methodology for deriving rank order values is described as follows. First, the trend for each crop in each county was calculated as the percentage change observed between 1981 and 1996. If the trend for a particular crop was positive (increasing) in all counties, rank values from 1 to 8 were assigned to the counties in order from the lowest level of change to the greatest level. If the trend was negative in all counties, the rank values from 1 to 8 were assigned in order from the least negative to the most negative. In cases with both positive and negative trends, a value of 1

was assigned to that county where the absolute value of the two extremes of the range of values was a minimum. For example, if the change values ranged from a 50% decrease in production to a 20% increase, the county which had the 20% increase was assigned a rank order value of 1 while the county which had the 50% decrease was assigned a rank order value of 8. A higher rank order value therefore indicates a county with a relatively large change in the production level of the respective crop over the period of analysis. The cumulative rank order for a particular county was derived by summing the respective rank order values for each major crop. Counties with the highest cumulative rank orders are those exhibiting the greatest amount of change in overall crop production over the period of analysis.

Table 4.5: Reported Acreage for Major Crops in Eastern Ontario.

Category	1,000s of hectares			
Year	1981	1986	1991	1996
Cropland on Census Farms	518	488	479	497
Acreage to Specified Crops				
Grain Corn	70	73	83	97
Fodder Corn	54	38	28	26
Soybeans	2	6	14	40
Oats	39	24	17	9
Hay	282	261	270	271
Grains*	60	68	55	38
Sub-total	508	470	465	481
Fruit Crops			0.9	1.0
Vegetable Crops			1.7	2.0
Ratio of Major Crop Sub-total to Cropland	0.981	0.963	0.972	0.968

Data from Statistics Canada

* Winter Wheat, Barley & Mixed Grains.

Figure 4.4: Major Crop Trends in Eastern Ontario.

Source: Statistics Canada.

* This is the combination of Winter Wheat, Barley and Mixed Grains.

When the cumulative rank order is visualized with a two-class, equal-size polygon plot (Figure 4.5), it is obvious that crop production trends in Eastern Ontario also divide according to the CAS Region and the OSL Region counties. The visualization graphically highlights the pattern of two unique groups of counties. The four CAS counties, which have the lowest levels of overall change in crop production, are more similar to each other than they are to the four OSL counties and vice versa. Similarities in crop production trends indicate that they are either increasing or decreasing in concert and at a similar rate. Dissimilarities indicate either opposing trends or trends which are substantially different in magnitude.

Table 4.6 and Figure 4.6 show the same data as in Table 4.5 and Figure 4.4 respectively, but separately for the OSL Region and the CAS Region. Table 4.7 shows the acreage planted data for the major crops for 1996. A plot of the data for the seven field crops (Figure 4.7) shows that the four western counties had the lowest total acreage under these crops. Again, dividing the range into two equal-sized groups shows that the four major producers are the counties in the OSL Region.

The focus of this thesis is on grain corn production for ethanol. Figure 4.8 shows that the cumulative contribution to total grain corn acreage in Eastern Ontario for the OSL counties is 92% whereas the CAS counties contribute only 8%. With this observation, and with the preceding observations of differences in production trends on a county by county basis, it is concluded that overall, Eastern Ontario can be viewed as two separate agricultural production sub-regions that coincide with the two physically distinct sub-regions identified in Section 4.1.

Figure 4.5: Distribution of Similarities of Crop Production Trends - Eastern Ontario Counties.

Cumulative Rank Orders for Major Crops* 1981 to 1996.

County	Cum. Rank Values
Stormont, Dundas & Glengarry	35
Prescott & Russell	40
Leeds & Grenville	26
Ottawa-Carleton	39
Frontenac	19
Lennox & Addington	17
Lanark	20
Renfrew	20

* See text for methodology used to derive the cumulative rank order values.

Table 4.6: Reported Acreage for Major Crops in Sub-regions of Eastern Ontario (thousands of hectares).

CAS Region				
	1981	1986	1991	1996
Grain Corn	11.2	8.3	8.0	8.1
Fodder Corn	15.4	11.7	9.3	8.4
Soybeans	0.5	1.1	1.5	3.9
Oats	14.2	9.8	7.2	4.1
Hay	106.1	101.5	105.4	114.0
Grains*	21.1	21.3	18.6	15.7
Sub-total	168.6	153.7	149.9	154.2
% of EO Cropland	32.6	31.5	31.3	31.0
% of CAS Region Land	9.8	8.9	8.7	9.0
OSL Region				
	1981	1986	1991	1996
Grain Corn	59.1	64.8	74.6	88.7
Fodder Corn	38.6	26.0	18.3	17.2
Soybeans	2.0	4.6	12.2	36.2
Oats	24.8	14.6	9.6	5.2
Hay	175.7	159.8	164.3	156.8
Grains*	39.1	46.6	36.0	22.3
Sub-total	339.3	316.5	315.1	326.3
% of EO Cropland	65.5	64.8	65.8	65.7
% of OSL Region Land	29.4	27.4	27.3	28.3

Source: Statistics Canada - Catalogue No. 95-177-XPB

Table 4.7: Major Crop Acreage in Eastern Ontario in 1996.

	thousands of hectares						
	Grain Corn	Fod- der Corn	Soy beans	Oats	Hay	Grains *	Sub- total
Stormont, Dundas & Glengarry	42.2	6.6	17.4	1.5	50.0	7.5	125.3
Prescott & Russell	18.9	3.4	8.3	1.5	41.0	6.4	79.5
Ottawa-Carleton	18.8	3.9	8.1	1.1	29.6	4.5	65.9
Renfrew	1.6	2.8	0.6	2.4	42.1	6.3	55.7
Leeds & Grenville	8.7	3.2	2.4	1.1	36.1	4.0	55.6
Lennox & Addington	3.2	1.8	1.9	0.6	22.6	4.5	34.5
Lanark	2.4	2.0	1.2	0.6	24.8	2.7	33.7
Frontenac	0.9	1.9	0.2	0.5	24.5	2.3	30.3
Total	96.8	25.6	40.1	9.3	270.8	38.0	480.5

Source: Statistics Canada - Catalogue No. 95-177-XPB

* Includes Winter Wheat, Barley and Mixed Grains.

Figure 4.6: Comparison of Major Crop Trends Between the CAS and OSL Regions.

* Includes Winter Wheat, Barley and Mixed Grains.

Source: Statistics Canada - Catalogue No. 95-177-XPB

Figure 4.7: Field Crop Acreage in Eastern Ontario in 1996.

* Includes Winter Wheat, Barley and Mixed Grains.

Source: Statistics Canada - Catalogue No. 95-177-XPB

Figure 4.8: Cumulative Contribution to Eastern Ontario's Grain Corn Production* (1996)

* Based on acreage planted.

Source: Statistics Canada - Catalogue No. 95-177-XPB

5 RESEARCH FRAMEWORK: METHODS & IMPLEMENTATION

5.1 REVISITING THE RESEARCH PROBLEM

The foregoing discussion has established that anthropogenic greenhouse gas emissions are believed to be responsible for accelerating climate change and all its consequent positive and negative impacts on a global scale. It has also become apparent that the combustion of fossil fuels in automobiles and light-duty trucks is a major contributor to greenhouse gas emissions in Canada. If the types of problems commonly associated with climate change are to be avoided or minimized, it is imperative that greenhouse gas emissions be reduced. More widespread use of renewable fuels in the transportation sector, and the use of ethanol-blend fuels for automobile transport in particular, represents one approach for addressing this serious environmental concern.

This research investigates the potential for a renewable feedstock-based ethanol industry in Eastern Ontario. In the near term, i.e., prior to 2010, it appears that the only feasible source of ethanol would be from the fermentation of grain corn. Grain corn is currently grown in Eastern Ontario in considerable quantities that are primarily (most likely) used for conventional corn-derived products. Since there is not yet a regional, large-scale ethanol plant in Eastern Ontario (see Section 3.2), it is reasonable to assume that only a very small percentage of the region's pre-1998 grain corn production, if any, has been used for ethanol production. It has also been confirmed that if ethanol-blend fuels are to contribute significantly to reducing greenhouse gas emissions, ethanol production in Canada will have to be increased by a minimum ten to fifteen times current levels (see Section 3.2). In the Eastern

Ontario region, such a requirement would be expected to stimulate considerable increases in grain corn production.

In the context of the agricultural sector in Eastern Ontario, an important question therefore is “can sufficient quantities of grain corn be produced to supply the feedstock requirements of a potentially rapidly expanding corn-based ethanol industry?” More specifically, “what is the upper limit of grain corn production capacity that could be realized given the limitations on the amount of land readily available for agriculture and assuming that existing competing demands on the land resource base for growing crops for all other uses would continue?” Fundamentally, this is a question of optimally allocating limited or scarce resources (e.g., agricultural land) to meet the multiple and varying demands for agricultural commodities. The climate change issue may therefore be seen as another “layer” on a conventional optimal resource allocation problem.

Mathematical or linear programming (LP) is a proven approach for modeling agricultural land allocation and/or food supply issues on a regional scale (Heady and Srivastava, 1975; Hazell and Norton, 1986; Brklacich, 1989; Smit et al., 1991). It will therefore be used in this research to evaluate the potential for Eastern Ontario to adapt to a potentially increasing demand for corn. The linear programming methodology is described in the following section as a basis for understanding the structure and nature of the subsequent land use model developed for Eastern Ontario. The remainder of this section summarizes the application of LP to agricultural land use issues and presents the specific LP model developed for the agricultural sector of Eastern Ontario.

5.2 THE APPLICATION OF LINEAR PROGRAMMING TO AGRICULTURAL LAND USE ANALYSIS

Linear programming is “concerned with the optimal allocation of scarce resources among competing ends” (Dykstra, 1984, p. 12). It has been widely used in the field of agricultural economics since the mid-1950s because, for various reasons, “the programming model provides a rather natural framework for organizing quantitative information about the supply side of agriculture...” (Hazell and Norton, 1986, p. 4). One particularly common use of resource allocation models is to answer questions concerning the potential of agricultural systems to meet demands/targets for food production (e.g., Smit et al., 1991). The approach can be applied over a wide range of scales, from single farms to a macro-scale regional problems. Specifically, questions such as the following may be posed.

- what are the options or alternatives for resource use?
- how much flexibility or robustness exists within any given agricultural production system?
- what is the potential to expand the agricultural production base?
- how might changes in biophysical and/or socio-economic condition (e.g., climate changes or pressures to produce a feedstock crop for the production of an alternative fuel) impact agricultural prospects?

It is important to realize however, that the ultimate purpose of resource allocation modeling “is insight, not numbers” (Dykstra, 1984, p.12). The use of linear programming provides a decision-maker with specific quantitative information about

a problem that may be employed, along with other relevant information, to make land use decisions.

The fundamental elements of resource allocation models are 1) a set of constraint functions and 2) an objective function. Constraint functions, or simply constraints, comprise a series of linear expressions that specify pertinent limitations applicable to the system being modeled. Constraints should be obvious and quantifiable. Such constraints may be specified limits on the availability of input resources (e.g., the acreage of land within a certain region) or on the demand for production within the system (e.g., the total production of a crop must not be less than a preset amount). In addition, constraints may describe functional limits within the production system (e.g., maintaining a certain ratio of production of one crop to that of another) or production/resource use limits included to ensure environmental and/or resource protection and preservation.

Taken together, the constraint set determines whether the available resources and limitations on their use are sufficient to meet the specified production requirements. In the terminology of linear programming, the constraint set is used to determine if a feasible "space" for the particular system being modeled exists. If the programming model shows that there is no feasible space, it implies that the constraints are too limiting within the system and the specified output requirements cannot be met. When it is possible to meet all of the specified conditions, there are likely to be many feasible solutions to the resource allocation problem. The objective function of the model identifies a feasible solution that is optimal in some way. This optimal solution is identified by either minimizing or maximizing some feature of the system (e.g.,

maximize profits, minimize resource utilization, maximize production potential or minimize land use change).

The objective function of a resource allocation model relates activity or decision variables within the system in an expression statement for the selected optimization. The primary characteristic of the objective function is that it is quantitative. A good objective function is clear, relatively easy to formulate and non-controversial. In conventional resource allocation models, the objective function will typically be expressed in terms of economic return. This means that all relevant constraints, including those addressing environmental concerns, must be formulated in relation to the relevant economic variables.

In the general case, a linear programming model for resource allocation may be specified as follows:

1. Identify the objective function that maximizes or minimizes z , such that

$$z = \sum_{j=1}^N C_j x_j$$

for N activity variables (x_j 's) and where C_j is a coefficient representing the economic margin for each unit of activity j

2. subject to the constraint relationships that specify that

$$\sum_{j=1}^M y_{ij} x_j \left\{ \begin{array}{l} \leq \\ = \\ \geq \end{array} \right\} B_i$$

for $i = 1$ to M constraints and where y_{ij} is a technological coefficient for variable j and constraint i and B_i is the right hand side (RHS) constant for constraint i

3. and $x_j \geq 0$ for $j = 1$ to N .

Although a “conventional resource allocation model” usually has its objective function expressed in a way that maximizes economic return or minimized economic costs, objective functions can also be specified that focus on the productive potential or the capacity of the land resource base for agriculture compared to selected base line or target values. For example, Smit et al. (1991) looked at food production in Ontario from the point of view of estimating how various sets of production targets can be met or exceeded in a series of different scenarios of land availability, quality and productivity (e.g., increasing crop productivity, increasing urban expansion, etc.) Eleven geographic regions were defined by both political and climatological boundaries and within each of these, up to seven possible land (soil) types were considered. The analysis considered nineteen crop products and eight livestock products to comprise a total of twenty-seven land use activities.

A useful feature of linear programming models is the ability to conduct various sensitivity analyses. There are a number of ways to conduct sensitivity analyses; for example, by changing the form of the objective function or by tightening or relaxing some of the technical coefficients or resource limitations expressed in the constraint function(s). For example, if an optimal solution is found, it may not be readily apparent to what extent additional, and possibly quite distinct, feasible solutions may

exist. Sensitivity analysis permits an analyst to gain insight into such and other relevant questions. The Smit et al., (1991) example mentioned above was primarily a sensitivity analysis carried out to identify the degree of flexibility about Ontario's food production potential under variable inputs and demands.

5.3 DEVELOPMENT OF THE AGRICULTURAL LAND USE MODEL FOR EASTERN ONTARIO

There are four fundamental organizational aspects, or phases, involved in the development of the agricultural land use LP model to be employed in this analytical endeavor as follows:

- Identification and specification of guidelines for the development of the model.
- Specification of the structure of the model itself.
- Specification of the scenarios to be modeled in the analysis.
- Identification and enumeration of the input data requirements for the model.

The functional and structural relationships between these components that ultimately lead to model output are portrayed schematically in Figure 5.1. The following subsections of this thesis individually describe the above stages in the development of the subject agricultural land use model.

Figure 5.1: Structural Relationships in the Development of a Land Use Model for Eastern Ontario.

5.3.1 GUIDELINES FOR MODEL DEVELOPMENT

As stated in the introduction to this thesis, Eastern Ontario is selected as a case study to evaluate the prospects for producing sufficient feedstock materials for the ethanol-for-fuel industry. It is considered to be a manageable, yet a sizable enough producing region to make the results of the analysis applicable in the broad context of sectorized contributions to greenhouse gas emission reductions³⁷. The region is currently a major contributor to Ontario's agricultural economy, including substantial grain corn production (OMAFRA, 1996) and there is some evidence that regional agricultural production levels could be increased (LEG, 1984). The percentage of Ontario's grain corn grown in Eastern Ontario has increased substantially in the past 15 years. In fact, its relative contribution to the province's corn production more than doubled during this period – from 6.5% in 1981 to 13.8% in 1996.

The production of grain corn for ethanol is but one of a number of demands for agricultural products in Eastern Ontario. The agricultural land use model must therefore be structured in such a way that it can consider production levels for other selected agricultural products on a region-wide basis.

In Section 4.3, it was concluded that the most appropriate way of representing the region from an agricultural perspective is according to the OSL and CAS sub-regions. The diversity of crop production patterns observed in Eastern Ontario is such that if

³⁷ In 1996, the population of Eastern Ontario was 1.307 million. This is just over 12% of Ontario's population and 4.53% of Canada's for the same year.

the region were to be treated as a single unit, certain intra-regional differences would be overlooked. Within the respective sub-regions, a reasonable degree of homogeneity exists, suggesting that the region need not be treated according to its eight individual political units for analytical purposes. Consequently, the agricultural land use model for Eastern Ontario should be structured on the two basic geographic units. In order to capture the effect of natural “inertia” within agricultural systems, the model should specify some minimal requirements for intra-regional crop production (all crops). It is not expected that large-scale reversals of land use patterns, where all production of a particular crop is allocated to only one of the sub-regions, would occur within the rather short time horizon for the analysis. It may also be expected that a portion of the crops produced in a particular sub-region is used for local requirements, especially for hay and fodder corn and that neither sub-region would therefore become fully dependant on the other for such a crop.

As further portrayed in Section 4.3, nearly all of the land classed as cropland in Eastern Ontario is used for eight major crops – grain corn, fodder corn, soybeans, hay, winter wheat, oats, barley and mixed grains. For example, in 1996, the sub-total of the acreage reported on census farms for the above major crops was 481 thousand hectares (Statistics Canada, 1996). The total amount of land reported as cropland that year was 497 thousand hectares. The model can therefore be set up to consider only these eight major crops. It is assumed that the agricultural sector in Eastern Ontario can continue to make a small fraction of cropland available for other crop products regardless of whether potential pressures for increases in any of the major crops are brought to bear on the system.

Land resources for agricultural crops in Eastern Ontario are finite. As indicated in Section 4.2, the land available for agriculture in Eastern Ontario can be disaggregated into seven basic land types (LEG, 1984). Land type F is considered unsuitable for crops and there is such a small amount of land type G that it is of little consequence to exclude it from the analysis. Although this latter land type is suitable for crops and has similar biophysical characteristics as land type A, it is generally steeper terrain and is therefore more problematic in terms of use for crop production. Consequently, the model can be structured to include only land types A through E. Furthermore, the model must ensure that the maximum amount of land that would be allocated in the various scenarios considered for the eight major crops does not exceed that which is available.

Because the practice of crop monoculture is known to be an environmental threat and cannot be sustained over the long term (LEG, 1984), crops are usually grown in some kind of rotation sequence. Crop rotation has a number of benefits including soil protection and the disruption of crop disease and pest cycles. A typical crop rotation plan consists of two phases: the depleting and the replenishing phases. The depleting phase represents the cultivation of crop(s) that if grown continuously would result in accelerated and unacceptable levels of soil erosion and/or elevated risk of disease or pest outbreaks. Both of these factors would ultimately tend to reduce crop quality and to suppress yields. When replenishing crops are cultivated in rotation with depleting crops, soil erosion rates are less likely to exceed soil development rates over the long run and pest and disease damage may be minimized or avoided. The total length of the rotation period in years, the maximum allowable number of years of continuous production of specific depleting crops and the minimum number

of years that a suitable replenishing crop is required are all determined by certain inherent characteristics of the land, by the land management practices used during the production of the depleting crop and by the capacity of the particular replenishing crop to rejuvenate soil quality and/or to break pest/disease cycles. On this basis, land preservation considerations must be built into the agricultural land use model for Eastern Ontario. Without such provision for crop rotation, the model could yield results that cannot, or would not, be sustained in reality.

The specific interest in this research is in assessing the inherent potential of the available land resources in Eastern Ontario to satisfy increasing production demands for grain corn for ethanol production while at the same time continuing to meet existing demands for the production of all the major crops. The analysis is therefore not so much interested in the economic aspects of various agricultural scenarios, but in the feasibility of the resource base being able to sustain the demands of future crop production requirements. On this basis, and because the land available for crops in Eastern Ontario is a finite resource, an objective function in the resource allocation model that determines the minimum possible area of land needed to produce all the specified quantities of crop products is considered the most appropriate and suitable for this purpose. This objective function will identify the unique feasible solution, if any out of a potentially large number of feasible solutions that can be accommodated within the specified constraints imposed by the model. It is therefore a conservative model in that it will identify the most efficient land use pattern at the regional scale for meeting the specified production targets.

In this respect, the resource allocation model constitutes a preliminary analysis in that it examines the feasibility of the regional land base with respect to possible increases in crop demands. It represents a precursor to other more detailed levels of analysis that would examine the economic ramifications of any changes in land use patterns or the socio-economic desirability of alternative agricultural land use patterns suggested by the preliminary analysis. Hence, this analysis does not need to include economic variables. Rather, it provides a direct measure of land use potential relative to a set of scenarios and whether there might be sufficient land resources to meet future crop demands.

It is also important to restate that the proposed model is an evaluative tool, not a prescription for optimal land use. It constitutes an evaluation of the technical feasibility of using the available land resources to meet projected future agricultural demands, including non-food demands. It is not intended to prescribe land use options for any part of Eastern Ontario. From a practical viewpoint, the model and its application should be of interest at the regional scale by indicating whether the region as a whole has the productive capacity to meet future agricultural demands. In addition, it may be used to indicate how changes in land supply or agricultural requirements might alter future land use options. It is however, not applicable at a land use planning level nor are the results applicable to other regions. The model could be adapted to address similar land use questions in other regions or at other geographic scales, but these sorts of initiative represent fundamentally different resource use problems that are beyond the scope of this study.

The time frame applicable to this research (about 10 to 12 years) is consistent with the period over which rather substantial changes in agricultural land use can occur (see Section 4.3). Because the model used in this analysis is applied in a comparative static mode, i.e., two snapshots, it does not provide explicit information or insight into the land use change process required to move one set of conditions to another. Based on the recent land use history of the region, it is reasonable to speculate that further substantial shifts in land use could occur prior to 2010.

Because the time frame of interest concerning possible agricultural land use changes that might result from an increased demand for ethanol fuel is relatively short term, the analysis will be based on historic production data etc. Climatic changes brought about because of greenhouse gas emissions can be expected to occur over several decades; potential climate change-induced crop yield responses will therefore not be factored into the development of the model.

The remainder of this sub-section is included to acknowledge the potential of past and/or future urban growth to impact the current and projected amounts of available agricultural land in Eastern Ontario. Admittedly, there has quite likely been some portion of the 737 thousand hectares that was estimated to be available for crops by the LEG in 1984 that has since been converted to other land uses (e.g., to urban/residential expansion because of continued population growth). Similarly, it is reasonable to expect that between the present (1999) and the 2010 time frame of the Kyoto Protocol, some additional agricultural land will be turned over to other uses. However, in the subsequent analysis of the potential for increased grain corn production in Eastern Ontario, it will be assumed that any such changes that have

occurred, and that may yet occur, would be minor and negligible compared to the size of the overall land base. In other words, urban expansion in Eastern Ontario is not expected to have appreciably reduced the amount of land cleared and available for crops below the 1984 estimates. Similarly, urban expansion is not expected to significantly reduce land availability in the near future.

As discussed in the previous section, the quantities of cropland and improved land reported in census information have been relatively constant from 1981 through 1996. This observation supports the claim that the amount of land removed from the agricultural land base during this period for other uses is but a small fraction and quite possibly of a magnitude that is substantially less than the degree of uncertainty associated with either the census-based cropland data or the 1984 land resource availability estimates. Considering that the period of interest in the present analysis is comparatively short – only 14 years from 1996 to the end of 2010 – it is assumed that the observed stability trends could well continue through the intervening period and that, by extension, a similar constancy has also applied and will continue to apply to the various estimates of the quantities of the different land types cleared and available for crops as per the LEG (1984). Furthermore, since the land use model described herein is intended to be evaluative rather than prescriptive for optimal land use, some degree of variance, say in the order of 15% to 20%, between the estimates used for model inputs and the actual current or near-future quantities of available cropland would have little consequence on the validity or usefulness of the proposed analysis. In any event, updating the 1984 land type availability estimates – and it is difficult to speculate what kind of improvement could be achieved by doing so – is well beyond the scope of this research.

In summary, the degree to which the availability of agricultural land for crops in Eastern Ontario has been, or will continue to be affected by urban expansion is concluded to be minor – at least within the time frame of interest in the proposed analysis. Further, it is not expected that any uncertainty in this regard will detract from being able to complete the analysis or from its anticipated overall validity or usefulness.

5.3.2 MODEL SPECIFICATIONS

As stated in the preceding section, the present linear programming problem is best addressed with a model that minimizes the total area of land allocated to satisfy overall production requirements. Formulation of the agricultural land use model for Eastern Ontario includes the following three steps.

1. Identify the model's units of analysis (e.g., decision variables or unknowns, input parameters, coefficients and RHS values).
2. Specify the constraints.
3. Specify the objective function.

The requirements for each of these steps are summarized in the following sub-sections.

Units of Analysis

The units of analysis used in the LP model for agricultural land use in Eastern Ontario are presented in Table 5.1. The land units are specified in two spatial dimensions:

- the geographic region (i.e., the OSL and the CAS sub-regions) within Eastern Ontario ($r = 1, 2$) and
- the land type (A through E) ($t = 1, 2, 3, 4, 5$).

The land use activities, or the types of crops to be produced represent the eight major crops: grain corn, fodder corn, hay, soybeans, winter wheat, oats, barley and mixed grains³⁸ ($i = 1, 2, 3, 4, 5, 6, 7, 8$ respectively). These crops consistently occupy at least 95% of all land classed as cropland in Eastern Ontario (Table 4.5). On this basis, it may be assumed that the amount of land required for other agricultural uses, such as fruit and vegetable production, will always be available regardless of whether there are increasing or competing demands from the eight major crops.

In summary, the model is structured on two geographic regions, five land types in each region and with eight major crops that can be produced on each land type. Consequently, there will be a maximum of eighty decision variables in the model expressed as the allocation (a) for each crop (i) on each land type (t) in each sub-

³⁸ Assumed to consist consists of 40% oats and 60% barley.

Table 5.1: Agricultural Land Use Model for Eastern Ontario.

Model Component	Expression	
1. Units of Analysis		
a) Knowns		
Available Resources: – Geographic Region	r_1 (OSL Region) r_2 (CAS Region)	
– Land Types A_{rt} = Land Availability in Region $r = 1$ to 2 and on Land Type $t = 1$ to 5.	t_1 (Land Type A) t_4 (Land Type D) t_2 (Land Type B) t_5 (Land Type E) t_3 (Land Type C)	
Production Requirements: – Total Regional Crop Production Requirements (Q_i) – Sub-regional Crop Production Requirements (Q'_{ri}) – Crop Yield Coefficients (y_{rti}) for $i = 1$ to 8.	i_1 (Grain Corn) i_5 (Winter Wheat) i_2 (Fodder Corn) i_6 (Oats) i_3 (Soybeans) i_7 (Barley) i_4 (Hay) i_8 (Mixed Grains)	
b) Unknowns (Decision Variables)		
– Areas allocated to each crop on each land type in each geographic region	a_{rti}	
2. Constraints		
– Land availability limits	$\sum_{i=1}^8 a_{rt} - A_{rt} \leq 0$	(5.1)
– Overall crop production requirements	$\sum_{r=1}^2 \sum_{t=1}^5 a_{rti} \times y_{rti} - Q_i \geq 0$	(5.2)
– Sub-region crop production requirements	$\sum_{t=1}^5 a_{rti} \times y_{rti} - Q'_{ri} \geq 0$	(5.3)
– Environmental preservation requirements	$\sum_{i=4,6,7,8} a_{rti} - k \sum_{i=1,2,3} a_{rti} \geq 0$	(5.4)
– Non-negativity	$a_{rti} \geq 0$ for all r, t and i	(5.5)
3. Objective Function	minimize $z = \sum a_{rti}$	(5.6)

region (r) of Eastern Ontario). For example, $a_{1,1,1}$ represents the area allocated to grain corn on land type A in the OSL Region of Eastern Ontario.

Constraints

The constraints for the Eastern Ontario agricultural land use model are also presented in Table 5.1 and can be grouped into four primary sets as follows:

1. Land availability limits
2. Overall production requirements
3. Regional production requirements
4. Soils preservation requirements

The ten land availability constraints, five land types in each of two regions, stipulate that the sum of the areas allocated to the six crops on each land type in each region must be less than or equal to the total amount of each land type available in each of the two regions (A_{rt}). In other words, the model cannot allocate more land to the production of crops than is actually available. These constraints are expressed by Equation 5.1 in Table 5.1. For example, the sum of the areas devoted to all eight crops on land type E in the OSL Region ($A_{1,5}$) must be less than or equal to 203,000 hectares. See Section 5.3.4 for the other limitations on land type availability for the two regions.

The next set of constraints specifies production requirements (in tonnes) for Eastern Ontario as a whole. Since crop yields are variable according to land type, the total

production requirement will be made up of the production of each crop on each land type in each region. These constraints are expressed by saying that the total crop production requirement is the product of individual land areas allocated to a particular crop (a_{rti}) and the respective crop yield (y_{rti}) summed over all land types and over all regions for each crop (Equation 5.2). There will therefore be eight such production constraints, one for each crop. The constraint indicates that such production must meet a preset minimum level for the particular crop (Q_i). For example, when summed over both regions of Eastern Ontario and over all five land types, the areas of land allocated to grain corn times the yield of grain corn on the respective land type in the respective region must be greater than or equal to the specified production requirement for grain corn in Eastern Ontario in tonnes per year.

The third set of constraints specifies the sub-regional production requirements. These are the prescribed minimum quantities of each crop (Q'_{ri}) that must be retained within the respective sub-regions. The minimum regional production requirements will be set at 75% of the basic regional production requirements applicable to the various scenarios to be modeled **before** additional grain corn for ethanol is added. These constraints on the minimum regional production are expressed in a similar fashion as for the region as a whole. However, in this case there will be sixteen constraints (eight in each region) as expressed by Equation 5.3.

The fourth set of constraints ensures that the necessary environmental preservation considerations are incorporated into the model. Either of two basic approaches can be adopted for this purpose. One approach is to create a single new land use activity

("x") that consists of two (or more) crops as a composite land use activity. For example, if a particular land type requires one year of a depleting crop (say, grain corn at 6 tonnes per hectare) to be followed by at least two years of a replenishing crop (say, hay at 9 tonnes per hectare), then the productivity of the corn/hay composite would be 2 tonnes corn and 6 tonnes hay per hectare of that land type on an annual basis. This approach minimizes the size (number of rows) in the particular linear programming model. However, it is less flexible because a different composite land use will have to be specified each time that the land conservation constraints are changed.

The temporal dimension of the linear programming model used in this study is one year whereas crop rotations occur over multiple years. In order to capture the effect of typical multi-year (usually 3 or 4) rotation cycles, it is possible to assume that time equals space. This is the second approach for handling land conservation constraints in a programming model. For example, a four-year rotation cycle that includes two years in a depleting crop followed by two years in a replenishing crop can be represented in the model by imposing a constraint that requires that the area allocated to the depleting crop cannot exceed the area allocated to the designated replenishing crop. This approach, which is adopted for the present land use model, is more flexible for varying land use constraints during the analysis. However, it does cause the model to get somewhat larger.

Given the above assumptions, a general formula to represent environmental protection requirements can be specified as follows. To capture the essence of a crop rotation sequence, the area to be allocated to all replenishing crops must be at

least equal to the total area allocated to all depleting crops times a specific rotation factor (k), where k = the minimum number of years for replenishing crops divided by the maximum number of consecutive years for depleting crops. This constraint is shown in algebraic form in Equations 5.4 in Table 5.1. The rotation plans to be built into the model are specified in Section 5.3.4 on Data Requirements.

The specification of the non-negativity constraints (Equation 5.5) is standard procedure in linear programming and is done to ensure that a model will not return feasible solutions containing negative allocations to the decision variables.

Objective Function

Having specified the above constraints, and given that the nature of the analysis is evaluative rather than prescriptive, the objective function of the model is formulated so that it will minimize the total land area allocated to the major crops in Eastern Ontario (z). The sum of all areas allocated to all crops on all land types in both sub-regions of Eastern Ontario is to be the minimum possible combination out of the total land area available (Equation 5.6) which will satisfy all the constraints imposed on the model.

Solutions to linear programming models for resource allocation analyses can be derived numerically with a procedure known as the **simplex method** (Wu and Coppins, 1981). The optimal solution is found by using an iterative procedure, or algorithm, which is based on computations involving matrix algebra techniques. A number of commercial software products are available which include routines to

compute solutions to linear programming models of this sort. In this analysis, the Microsoft® Excel 97 tool **Solver** will be used to carry out the linear optimization. It is a linear programming tool which uses the simplex method with bounds on the variables, and the branch-and-bound method for linear and integer problems developed by Frontline Systems, Inc. of Incline Village, NV.

5.3.3 SPECIFICATION OF AGRICULTURAL LAND USE SCENARIOS

Scenario Analysis and Modeling

The term “scenario” is used to describe the set of conditions governing resource use. Ideally, the scenario would include assumptions about all factors that ultimately influence the use of a particular resource. Although this is impossible, as a minimum, a scenario must consider all of the parameters that are captured by a resource use model. In the context of the agricultural land use model specified for this research (see Section 5.3.2), a scenario includes estimates of:

- crop yields,
- regional & sub-regional requirements for the production of 8 crops,
- ethanol production targets,
- land availability for the production of agricultural crops, and
- land conservation practices that will maintain soil quality over the long term.

Scenario analyses have been used extensively in conjunction with linear programming models to explore the resource implications of uncertain futures (e.g.,

Smit et al., 1979). A scenario represents a “snap shot” at a particular time (e.g., the present, 10 years in the future, etc.) and model output obtained under two or more scenarios provides a basis for comparative static assessments. While these comparisons do not detail the pathway of change between the two periods, they do provide a basis for evaluating the extent to which the specified set of conditions might alter future options for resource use.

The specification of a base scenario is the usual starting point for scenario analyses and output derived from a base run of the model becomes one of the standards against which subsequent model runs are compared. A base scenario is often derived from current conditions.

Studies investigating possible future uses of resources regularly employ multiple scenarios to capture and bound uncertainty. Even studies with time horizons as short as 5 years must grapple with uncertainty. Longer time frames usually imply greater levels of uncertainty and with it, a concomitant increase in the number of scenarios that need to be considered. There are at least three approaches for developing scenarios to depict future conditions.

The “Incremental Change” approach applies a predetermined level of positive or negative change to a selected model parameter. All other conditions – all the various model parameters – are held constant while the selected condition is increased or decreased in equal-sized steps. This approach is generally not intended to predict a likely future, but its application can be used to:

- gauge the sensitivity of a resource system to change in the selected parameter, and
- estimate the maximum potential levels of regional production for the selected parameter under current conditions.

The “Status Quo Growth” approach develops scenarios by extrapolating recent trends into the future and is sometimes referred to as the “Do Nothing” scenario in the impact assessment literature (e.g., Munn, 1979; Marriott, 1997). It facilitates the establishment of a future baseline against which other future scenarios can be compared. It is reasonable to expect that a dynamic resource use system such as agricultural land use will undergo many changes even over a relatively short time period. In the absence of any other specific information, recent trend changes can be applied to base conditions to describe a status quo growth scenario.

The “Comprehensive Growth” approach incorporates data from exogenous studies of future growth and specifies change levels for multiple model properties. Several exogenous studies can be used to establish the possible boundaries of change that in turn provides a basis for estimating the range of options for future resource use. A comparison of model outputs obtained under the “Comprehensive Growth” scenarios to those obtained under the “Status Quo Growth” approach can be made to estimate the extent to which resource use options might change if the conditions specified under the “Comprehensive Growth” scenario were in fact implemented.

Scenario Specification

The analytical component of this thesis is organized according to an initial set of pre-defined themes or levels as follows:

- Scenarios 1A and 1B represent base (current) conditions and the maximum potential for grain corn under the current conditions.
- Scenarios 2A and 2B are status quo growth (SQG) extrapolations of recent trends applied to the base level and the maximum potential for grain corn under conditions of a possible near-term future.
- Scenarios 3A, 3B and 3C represent specific ethanol development levels under conditions similar to those in scenario 2A.

Additional scenarios may be specified and modeled based on the analysis of the results of the initial modeling runs. Conditions and assumptions underpinning the various initial scenarios are outlined in Table 5.2 and they are further described in this section.

In summary, the above scenarios include one that represents the current expression of the agricultural system of Eastern Ontario as well as various future scenarios that are derived using the approaches outlined above. In keeping with the nature of the model and its objective function, the scenarios are to be used for comparative static evaluations and not for predictive purposes.

Table 5.2: SCENARIO SPECIFICATION

Model Parameter	Scenario Description (Scenario No.)			
	Current or Base (No. 1A)	Maximum Grain Corn Production Capacity (No. 1B)	Status Quo Growth (No. 2A)	Status Quo Growth Maximum Grain Corn Production Capacity (No. 2B)
Land Availability	• Estimates from LEG (1984)			
Land Conservation	• Recommended Soil Conservation Practices			
Crop Yields	• 1991-1996 Estimates			
Crop Production Requirements (excluding grain corn)	<ul style="list-style-type: none"> • Region: 91-96 Levels • Sub-region: 75% of 91-96 Levels • Trend increases beyond 1991-1996 • Region: Trends continued beyond 91-96 • Sub-region: 75 % of new levels 			
Grain Corn Production Requirements	<ul style="list-style-type: none"> • Region: 91-96 Levels • Sub-region: 75% of 91-96 Levels 	<ul style="list-style-type: none"> • Region: Maximize Grain Corn • Sub-region: 75% of 91-96 Levels 	<ul style="list-style-type: none"> • Region: Trend increases beyond 91-96 • Sub-region: 75% of new levels 	<ul style="list-style-type: none"> • Region: Maximize Grain Corn • Sub-region: 75% of new levels
Regional Ethanol Production Requirements	<ul style="list-style-type: none"> • No Additional Requirements 	<ul style="list-style-type: none"> • Inferred from Maximized Grain Corn Production 	<ul style="list-style-type: none"> • No Additional Requirements 	<ul style="list-style-type: none"> • Inferred from Maximized Grain Corn Production
				<ul style="list-style-type: none"> • Region: Inferred from ethanol requirements • Sub-region: 75% of new levels • Ethanol Market Penetration <ul style="list-style-type: none"> A) Minimal (5%) B) Moderate (10%) C) Extensive (31%)

NOTES: Procedures, data and assumptions employed to estimate crop yield, production requirements, and grain corn-ethanol presented in Section 5.3.4. Suggested ethanol market penetration percentages are on an energy equivalent basis.

Scenario 1A: Current Conditions (Base Case Scenario)

Applicable data on the amounts of land available for crops, crop yield coefficients, crop production requirements and crop rotation specifications were obtained and analyzed to develop this scenario so that it reflects average or typical conditions that existed in Eastern Ontario during the period 1991 through 1996³⁹. At the regional scale, model output derived from this scenario provides a quantitative estimate of the agricultural production capacity, or the potential, which is presently held in reserve. This agricultural production capacity would theoretically be available for any feasible use, either more production of any or all of the major crops, new production of other crops (agro-climatic and edaphic conditions permitting) or some combination of these options. The production potential will be presented both in absolute terms (hectares of land available) and as a fraction of the total resource base. The extent of the agricultural production potential under the base case scenario can therefore serve as a reference for the results of the other scenarios.

Scenario 1B: Maximum Grain Corn Production Capacity

Under this scenario, all but one of the model input parameters are held constant at levels set for Scenario 1A. Regional grain corn production will be increased incrementally by steps of 200,000 tonnes while all other parameters remain fixed at current levels. The land use model is executed in an iterative fashion until all available land resources are allocated. This application of the land use model

³⁹ Data, assumptions & methods used to estimate crop yields, land availability, etc. are presented Section 5.3.4.

therefore provides an estimate of the maximum amount of grain corn that could theoretically be produced under current conditions, that is, when all of the existing crop production demands are maintained at current levels. This estimate of “excess” grain corn capacity can then be converted into an ethanol equivalent production volume. Overall then, this scenario provides an estimate of the maximum production potential for ethanol in Eastern Ontario under current conditions. As such, it provides a convenient point of comparison for ethanol production rates projected under alternate scenarios.

Scenario 2A: Status Quo Growth

The Status Quo Growth scenario extends recent agricultural trends forward from 1991 – 1996 levels for approximately 15 years to 2010. This scenario is comprehensive in the sense that multiple changes to model parameters are invoked but the underlying causes for these adjustments remain outside the scope of this analysis. The scenario also recognizes explicitly that substantial shifts can be expected in Eastern Ontario’s agricultural sector over a 15-year time frame. The shifts employed here are consistent with the direction and magnitude of changes observed over the most recent 21-year period. Overall, Scenario 2A provides a future baseline against which alternate future scenarios can be compared. Key changes to conditions specified under Scenario 1A include increases to some crop yield coefficients and increases or decreases to various crop production requirements. Data, assumptions and methods to estimate 2010 values for each of these parameters are presented in Section 5.3.4.

Scenario 2B: Status Quo Maximum Grain Corn Potential

Under this scenario, all but one of the model input parameters are held constant at the same levels set for Scenario 2A. Regional grain corn production will be increased incrementally by steps of 200,000 tonnes while all other parameters remain fixed at current levels. The land use model is executed in an iterative fashion until all available land resources are allocated. Output from this scenario therefore provides an estimate of the maximum amount of grain corn that could theoretically be produced under conditions that could reasonably exist in 2010, i.e., with all the crop production requirements, except for grain corn for ethanol, maintained at the levels projected for 2010 in the Status Quo Growth scenario (2A).

Scenarios 3A, 3B & 3C: Ethanol Development Scenarios

Future scenarios including growth in ethanol production will be evaluated by specifying various levels of additional grain corn production over and above that specified in the Status Quo Growth scenario (No. 2A). Exogenous data will be used to set limits for estimating options for future resource use. Of relevance to this study are various references that consider greenhouse gas emission reduction targets. Since the use of ethanol as a motor fuel is seen as a means of reducing greenhouse gas emissions, its contribution towards such reduction targets can be evaluated in terms of the degree of market penetration expected with any given level of ethanol production and the corresponding requirements for grain corn.

The approach employed here is to develop a number of scenarios that span a range of ethanol futures that extend from a minimal level to a relatively extensive level of

market penetration. Uncertainties with respect to potential ethanol requirements include:

- the extent to which the further use of ethanol fuel will be part of federal/provincial strategies for reducing greenhouse gas emissions in the transportation sector.
- the degree of greenhouse gas emission reduction that can be expected by using ethanol (Section 3.3).
- the rate at which agricultural systems could respond to sudden and substantial increases in grain corn demands.

There is at present no clear indication as to the potential role of ethanol within Canada's national greenhouse gas emission reduction strategy. Nevertheless, the David Suzuki Foundation and the Pembina Institute for Alternative Development (1998) have jointly recommended that the federal government mandate a 5% renewable energy content target for all motor fuels as one component of its overall greenhouse gas emission reduction strategy⁴⁰. In addition, the Kyoto Protocol commits Canada to reducing its greenhouse gas emissions to 6% below 1990 levels by 2010. These external quantitative guidelines will be used as starting points for developing a range of future ethanol scenarios for the land use modeling effort.

Natural Resources Canada (1997) predicts that gasoline consumption will rise by 13.4% between 1995 and 2010. This equates to about 36.9 billion litres, or 1,279

⁴⁰ In these scenarios, it is assumed that the various levels of market penetration by ethanol are on an energy equivalent basis. On a volumetric basis, ethanol has about 61% of the energy density of gasoline. A 5% energy contribution would therefore require an approximate 8% volume penetration.

PetaJoules energy equivalent, for automobiles and light trucks. If 5% of this energy is to be from ethanol, Canada's annual production capacity will have to increase to approximately 3 billion litres. This is about 13 times the ethanol capacity available in 1998 or about five times the capacity expected to be available by the end of 2000 (as shown in Table 3.1).

Scenario 3A: Minimal Market Penetration (~5%)

A 5% ethanol market penetration is equivalent to the circumstance that approximately 80% of all cars and light trucks would be using E10 fuel by 2010. This is considered a realistically and readily achievable solution; one that only requires its incorporation into appropriate government policy and a concomitant promotional effort. There are no technical barriers with respect to vehicles and it is expected that the required level of ethanol production could comfortably be put in place by 2010. It would require about five times the ethanol production level expected to be available, on a national basis, by the end of 2000. This minimal level of market penetration by ethanol is not expected to negatively impact the conventional fuel industry.

Scenario 3B: Moderate Market Penetration (~10%)

At twice the market penetration level suggested by the David Suzuki Foundation and the Pembina Institute for Alternative Development (1998), it is necessary to assume that the majority (~90%) of cars and light trucks will use E10 and that a smaller fraction (at least 8%) will be using E85 by 2010. A scenario where ethanol comprises 10% of all motor fuel requirements (16% by volume) is considered a

moderately achievable solution within the current technical and economic contexts. With E85 vehicle technology becoming available in the US in 1998, it seems reasonable to speculate that by 2010, some incipient level of introduction in Canada could also be realized if desired. The requirement to increase the national ethanol production capacity under this scenario to about ten times the capacity expected to be available by the end of 2000 translates into an installed regional capacity of approximately 275 million litres per year. On the assumption that it takes about 3 years⁴¹ to construct an ethanol plant with a capacity in the order of 100 million litres per year, it is considered safe to speculate that about three such plants could technically be constructed in Eastern Ontario by 2010. In practice, it will largely depend on the prevailing incentive to make ethanol an essential and substantial part of the national strategy for reducing greenhouse gas emissions. Lastly, at 10%, the impact on the conventional fuel industry is still considered relatively minor.

Scenario 3C: Extensive Market Penetration (~30%)

Canada's commitment under the Kyoto Protocol is to reduce greenhouse gas emissions to 6% below 1990 levels by 2010. As pointed out in Section 2.6, the vehicles that could be using ethanol fuels currently contribute about 15% to the national greenhouse gas inventory. It may therefore be reasonable to suggest that, as a start, this sector should at least contribute 15% to the emission reduction needed to achieve the Kyoto Protocol target. As also indicated in Section 2.6, Canada's annual emissions will have to decrease by about 103 Megatonnes (Mt) from the level

⁴¹ This conclusion is based on the review of various references relevant to the ethanol-for-fuel industry, for example, Clark and Stumborg (1996) and the Canadian Renewable Fuels Association (1998b).

projected for the year 2000 by 2010. This means that the vehicles that could use ethanol fuels would have to cut about 15 Mt of greenhouse gas emissions from the national annual inventory; from about 100 Mt per year to about 85 Mt per year. In other words, for cars and light trucks to reduce greenhouse gas emissions to 6% below their 1990 levels, overall reductions of about 15 Mt annually would have to be realized in this sector. Eastern Ontario's share of these emission reduction targets, based on population, is 4.7 Mt per year (overall) and 0.7 Mt per year (cars and light trucks sector).

In Section 3.3, it was stated that the absolute use of E10 fuel Canada-wide, could reduce greenhouse gas emissions by about 2 Mt to 4 Mt annually. If it is assumed that the eventual realized benefit might be the mid-point of this range, E10 usage at just over 80% saturation (as in Scenario 3A) can be expected to reduce emissions by about 2.5 Mt per year, or about one sixth of the 15 Mt gap for cars and light trucks. For ethanol to contribute the full 15 Mt reduction for cars and light trucks, a market penetration in the order of 30% on an energy basis or 50% on a volumetric basis would therefore be required. This scenario (3C) would require just over 50% of all cars and light trucks to be E85 vehicles by 2010 (with the remainder being E10 vehicles). At this level of ethanol penetration, it becomes impractical to speculate concerning the possibility that such a greenhouse gas mitigation strategy could be realized by 2010. The necessary socio-economic changes are especially substantial and it is concluded that there is little merit in trying to predict, if indeed it would be possible to do so at present, whether the motor vehicle industry could adapt to provide the required technology mix by 2010, whether the national ethanol industry could be expanded to over 30 times the capacity expected to be available by the end of 2000 or whether the impact on the conventional fuels industry would be

acceptable. Furthermore, it is hard to anticipate the kinds of pressures or policies that may be proposed or instituted in the future to deal with a possibly more and more urgent need to reduce emissions. Nevertheless, it is considered useful to also consider ethanol and feedstock production requirements with this kind of radical greenhouse gas emission reduction objective. It is expected to help in hypothesizing over the potential limitations of ethanol-blended fuels in the context of contributing to the reduction of national greenhouse gas emissions.

In summary, ethanol requirements increase across scenarios 3A, 3B and 3C. It is important to note that the first of these two scenarios are simply based on a suggested renewable energy contents in motor fuel. While these levels (5% and 10% respectively) are somewhat arbitrary, it has been shown that they represent plausible futures with respect to automotive transportation. In contrast, the transportation options implied in scenario 3C are based on meeting a specified greenhouse gas emission reduction target (15 Mt per year). As noted in Section 3.3, the precise level of benefit ascribed to ethanol produced from grain corn is, at present, not firmly established or universally accepted and it may be expected that it will continue to be revised and/or variously reported with time. If at any time in the future, the actual benefit is demonstrated or generally accepted to be greater than or less than that specified for scenario 3C, the percentage market penetration of ethanol would have to be adjusted to maintain the specified level of greenhouse gas emission reduction. In other words, for ethanol to contribute the entire share of the 6% emission reduction target in the Kyoto Protocol for the cars and light trucks sector under this scenario, it must be demonstrated that ethanol's greenhouse gas reduction benefit is at least 46% less than that of conventional gasoline on an energy equivalent basis.

The grain corn production requirements and the corresponding ethanol production rates for the three ethanol development scenarios are presented in Section 5.3.4.

5.3.4 DATA

Four basic kinds of input data are required for the land use model. These are land type availability (hectares), crop yield coefficients (tonnes/hectare), regional and sub-regional crop production requirements (tonnes) and crop rotation factors. The necessary data are derived from two main sources: studies by the Land Evaluation Group of the University of Guelph were consulted for land availability and crop productivity estimates and for crop rotation factors. Annual reports from the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) were reviewed for crop production requirements and crop yield information. The data inputs for these categories are described below. In addition, the targets for ethanol and grain corn production for the various ethanol development scenarios need to be specified. As noted in the preceding section, these will be based on exogenous studies related to greenhouse gas emission reduction strategies in general. They are also specified in this section.

Land Availability.

The most comprehensive and applicable assessment of the amount of land cleared and available for agricultural is that done by the Land Evaluation Group (LEG, 1984) as identified in Section 4.2. Table 5.3, which is an extract of the data presented in Table 4.4, shows the quantities of available land for each of the five land types A

through E for the two sub-regions of Eastern Ontario. Because of the relatively short time horizon considered in this study, it is concluded that there will be no significant shifts in the quantity of land available for agriculture at the regional scale. The estimates in Table 5.3 will therefore be used for all scenarios analyzed.

Table 5.3: Maximum Amount of Land Available for Land Use Model for Major Crops in Eastern Ontario (1,000's of hectares).

	Land Type*						
	A	B	C	D	E	Sum	% **
OSL Region	114	50	114	38	203	519	45.0
CAS Region	60	33	58	7	52	210	12.2
Total	174	83	172	45	255	729	
OSL Region (%)	65.5	60.2	66.3	84.4	79.6	71.2	
CAS Region (%)	34.5	39.8	33.7	15.6	20.4	28.8	

Source: LEG, 1984.

* Column sums are not the same as in Table 4.4 because of rounding in the original data set. See Section 4.2 for a description of the classification system.

** Percent of total land base.

A comparison of the amount of land cleared and available for crops according to the LEG classification scheme and the amount of cropland reported by Statistics Canada from farm census data (see Section 4.3) shows that the sum of the latter acreage is about two thirds of the estimated available land for crops. This suggests that the current agricultural land use system of Eastern Ontario does not fully tax/utilize the resource potential of the land and that the prospects for growing additional grain corn for the production of ethanol could be significant.

Crop Yield Coefficients.

Crop yields for a particular region are influenced by a) the genetic makeup of the particular crop, b) the prevailing agro-climatic conditions of the region – all of Eastern Ontario receives 2,400 to 2,700 Corn Heat Units per season – and c) by a number of specific farm management practices. Constraint-free yields are used to represent the maximum genetic potential of a particular crop in a particular geographic region. For example, a study by the Land Evaluation Group (LEG) indicates that the constraint-free grain corn yield in Eastern Ontario is about 10.68 tonnes per hectare on a dry weight basis (LEG, 1985). Actual farm-attainable yields however, can be expected to be well below this constraint-free yield estimate. The combination of less-than-ideal soil moisture regimes – either excess or insufficient water – associated with the various land types and less-than-optimal farm management practices commonly result in yield reductions below the constraint-free level. Table 5.4 shows the farm-attainable yields estimated by the Land Evaluation Group for Eastern Ontario for the major crops for each of the land types A through E, assuming average weather conditions and average farm management practices (LEG, 1984). In the best case, the grain corn yield factor was estimated to be 5.8 tonnes per hectare, almost one half of the regional constraint-free yield value. This highlights the importance of the edaphic and management variables in estimating or predicting actual crop yields for a region under study.

Although the LEG (1984) yield estimates are expressly linked to the land types as described above, they date from a period about 20 years prior to the present assessment. It was therefore decided to examine whether there might be any basis on which to update them. The LEG (1984) yield estimates were benchmarked to

actual regional productivity data reported by OMAFRA over all land types for the period 1976 to 1981, except for soybeans where data are only available for the 1978 to 1981 period. The following methodology was therefore adopted to determine whether the land type productivity estimates could/should be revised prior to use in the land use model.

Table 5.4: Estimated Crop Productivity on Different Land Types in Eastern Ontario (tonnes per hectare) for the early 1980s.

	A	B	C	D	E
Winter Wheat	2.7	2.6	2.6	2.2	0.5
Oats	2.0	2.1	2.1	1.7	0.5
Barley	2.5	2.4	2.4	2.3	0.8
Mixed Grains*	2.3	2.3	2.3	2.1	0.7
Grain Corn	5.4	4.6	4.9	5.8	2.5
Fodder Corn	28.7	24.4	25.9	30.8	13
Hay	7.4	5.5	6.2	8.9	3.7
Soybeans	1.9	1.1	0	1.9	0

Source: Land Evaluation Group (1984).

*Assumed to be 60% barley and 40% oats.

First, average crop productivity values for the two periods 1976 through 1981 and 1991 through 1996 were calculated for the eight major crops using OMAFRA data. The ratios of these average yields for the 1991 through 1996 period to those for the period 1976 through 1981 were then separately determined for the OSL and CAS regions. Lastly, the original LEG yield estimates were multiplied by the respective ratio values to “update” the estimates to a more recent production period⁴². This yield ratio update approach is applied uniformly amongst the land types for each

⁴² Production periods spanning six crop years are used in this analysis because they include two census years where data are expected to be of greater quality.

crop, but separately for the two sub-regions. With no firm evidence to the contrary, it is assumed that any yield changes because of new technologies, improved varieties, etc. would not be concentrated on any particular land type(s). The productivity data for the two production periods and the respective ratios are shown in Table 5.5. The revised yield estimates are shown in Table 5.6 and will be used as “current” productivity input values for land use model for the Base (No. 1A) and the Maximum Grain Corn Production (No. 1B) scenarios.

Table 5.5: Average Crop Productivity in Eastern Ontario for Two Periods (tonnes per hectare).

	Period	OSL			CAS	
		1976-81	1991-96	Ratio*	1991-96	Ratio*
Winter Wheat		2.6	3.3	1.25	3.3	1.25
Oats		1.7	2.2	1.29	2.1	1.28
Barley		2.5	3.1	1.26	3.1	1.22
Mixed Grains		2.1	2.6	1.25	2.6	1.20
Grain Corn		4.8	6.8	1.42	5.8	1.22
Fodder Corn		26.6	24.2	0.91	24.8	0.93
Hay		5.8	6.1	1.06	5.9	1.02
Soybeans		2.0	2.5	1.26	2.5	1.26

Source: OMAFRA Publication 20: 1976 through 1981 and 1991 through 1996.

* 1991-96 value divided by 1976-81 value.

The actual observed 1976 through 1981 productivity values all lie within the range of the original LEG estimates, except for soybeans, for which the LEG estimates are in the range of 1.1 tonnes per hectare to 1.9 tonnes per hectare and the observed value, for 1978 through 1981, was 2.0 tonnes per hectare. This slight anomaly suggests that the LEG base data for soybeans are somewhat less reliable than the rest of the data – soybeans were just being introduced in Eastern Ontario in 1978. In the

absence of specific information to the contrary, the various updated LEG estimates will be therefore used as is for the respective yield coefficient inputs to the agricultural land use model.

Table 5.6: Revised Crop Productivity Estimates* on Land Types in Eastern Ontario (tonnes per hectare) for Base and Maximum Grain Corn Production Scenarios.

Land Type	A		B		C		D		E	
Region	OSL	CAS	OSL	CAS	OSL	CAS	OSL	CAS	OSL	CAS
Winter Wheat	3.39	3.39	3.26	3.26	3.26	3.26	2.76	2.76	0.63	0.63
Oats	2.59	2.55	2.72	2.68	2.72	2.68	2.20	2.17	0.65	0.64
Barley	3.14	3.06	3.02	2.94	3.02	2.94	2.89	2.82	1.01	0.98
Mixed Grains	2.86	2.77	2.84	2.74	2.84	2.74	2.57	2.48	0.85	0.82
Grain Corn	7.67	6.57	6.53	5.60	6.96	5.96	8.23	7.06	3.55	3.04
Fodder Corn	26.06	26.73	22.15	22.72	23.51	24.12	27.96	28.68	11.80	12.11
Hay	7.82	7.54	5.82	5.61	6.56	6.32	9.41	9.07	3.91	3.77
Soybeans	2.40	2.40	1.39	1.39	0.00	0.00	2.40	2.40	0.00	0.00

* Calculated by multiplying the LEG (1984) estimates in Table 5.4 by the respective update ratios shown in Table 5.5.

An analysis of the OMAFRA crop productivity data for the whole 21-year period 1976 through 1996 was also conducted to determine whether any of the observed increases shown in Table 5.5 represent statistically significant trends in this production parameter. Figures A.5b through A.12b in Appendix A show the yield trends for the eight major crops⁴³ for the CAS and OSL regions of Eastern Ontario. These trends were evaluated for statistical significance and grouped into the following three categories:

⁴³ Winter wheat, oats, barley, mixed grains, grain corn, fodder corn, soybeans and hay.

- No significant trend observed over entire 21-year period (either no linear trend or trend with R^2 regression value less than 0.5).
- Statistically significant trend evident over entire 21-year period (R^2 regression value greater than 0.5).
- A non-linear trend.

In addition, the production data were analyzed to determine if observed differences between the CAS Region and OSL Region are significant.

In cases where the productivity trends shown in Figures A5b through A12b (Appendix A) are strongly significant, it is considered reasonable to expect that further yield increases will continue to be realized in the near future. This condition applies to grain corn and soybeans – no other crop productivity trends were statistically significant. Given the relatively short term of the proposed analysis, it will simply be assumed that the additional yield increases for grain corn and soybeans will be one half as much again of the respective difference values shown in Table 5.5. These productivity values – to be used for the future Status Quo scenarios (Nos. 2A & 2B) and the Ethanol Development scenarios (Nos. 3A, B & C) – are shown in Table 5.7 and are derived by assuming a consistent and constant rate of yield increase will continue to be realized up to the 2006 to 2011 time frame. Since the period of analysis may be considered to start with the 1991 to 1996 period data, the average additional increase (up to the 2006/2011 period) will therefore apply to an interval half as long as the 1976/1981 to 1991/1996 period.

Table 5.7: Crop Productivity Estimates on Land Types in Eastern Ontario (tonnes per hectare) for All Future Modeling Scenarios.

Land Type	A		B		C		D		E	
Region	OSL	CAS	OSL	CAS	OSL	CAS	OSL	CAS	OSL	CAS
Grain Corn	8.80	7.18	7.50	6.12	7.99	6.52	9.45	7.71	4.08	3.33
Soybeans	2.64	2.64	1.53	1.53	0	0	2.64	2.64	0	0

Note: All other crop yield estimates for the future scenarios are the same as those in Table 5.6.

Although the updates of the yields for the cereal crops between the 1976/1981 and 1991/1996 periods are substantial (ranging from 20% to 28%), it will be assumed that there will not be any further increase during the period of analysis. The respective regressions are fairly weak, with R^2 values less than 0.5, and on close inspection of the trends, it may be concluded that there were step-wise increases in yield values in the mid-1980s and that they have been relatively constant since then. Consequently, the updated yield values will be retained for all scenarios. For fodder corn and hay, the changes in yield were less substantial and there were no trends at all. The updated yield values for these crops will therefore be retained for all scenarios as well.

Crop Production Requirements

The agricultural land use model specifies that on both a regional and a sub-regional basis, the production of the major crops must meet a prescribed minimum level for each crop. This is first to ensure that existing and continuing demands for the respective products from the region are reflected in model output and second, to capture system “inertia” by not allowing the model to present solutions with land use

patterns that are broadly at variance with existing patterns. Such major land use pattern changes are not ordinarily expected to occur within the kind of time frame applicable to this model (see Section 4.3).

A set of “current” and a set of future crop production levels (regional and sub-regional) for the relevant input requirements to the land use model have been derived from an analysis of applicable OMAFRA data for the period 1976 through 1996. The current production levels are intended to represent typical, relatively recent conditions and will therefore be used in the base case and Maximum Grain Corn Production scenarios. Future production levels would be representative of conditions that may be expected in 2010 and will therefore be used in the Status Quo Growth and Ethanol Development scenarios. The methodology employed to derive the current and future crop production input requirements for the land use model primarily seeks to identify whether significant trends can be observed in the relevant data sets. This methodology is summarized in Table 5.8. It shows the procedures used to derive the current and future production values from the various trend patterns encountered (see Figures A5a through A12a in Appendix A) and to which scenarios they apply.

The procedures used to set future production levels for the land use model are primarily based on the premise that significant trends may be expected to continue for some time into the near future, but because of uncertainty, it also seems inappropriate to expect that such trends would continue as they have been right through to 2010. To rationalize between these two possibilities, a relatively straightforward, median approach is used. For example, the periods 1976/1981 through 1991/1996 and 1991/1996 through 2010 both cover about 20 years.

Table 5.8: Summary of Methodology for Deriving Basic Crop Production Requirement Inputs.

Nature of Production Level Trend (1976 through 1996) ²	Method for Determining Basic Production Requirement Input to Model ¹	
	"Current" Levels for Base Case & Maximum Grain Corn Production Scenarios	"Future" Levels for Status Quo and Ethanol Development Scenarios
No significant trend evident over entire period (regression R^2 value < 0.5)	Utilize mean of relevant 1991 through 1996 data.	Continue to utilize mean of relevant 1991 through 1996 data.
Significant trend evident for entire period (regression R^2 value > 0.5)	Utilize value from trend (regression) line at 1996. Applies to oats and fodder corn (decreasing) in both sub-regions; to grain corn (increasing) in the OSL Region.	Set at 50% of current level for decreasing trends. ³ Applies to oats and fodder corn in both sub-regions.
		For increasing trends, add one half of the difference between the 1991 through 1996 mean and the 1976 through 1981 mean to the 1991 through 1996 mean. Applies only to Grain Corn in the OSL Region. ⁴
Non-linear (exponential) trend evident, especially in latter half of period.	Utilize actual 1996 production value. Only applies to soybeans (both sub-regions).	Add an additional 50% of the current level to the current level. Only applies to soybeans (both sub-regions).

Notes:

1. These methods determine the basic demand levels for the eight major crops, **excluding** any additional grain corn for ethanol.
2. See Figures A5a through A12a in Appendix A.
3. All significant decreasing trends are tending to zero production before 2010.
4. This approach is consistent with the methodology used to extrapolate increasing trends in crop yields.

Continuing the existing trend for grain corn production to a level with 50% additional growth is in practice extending the current trend to the midway point of the period 1991/1996 through 2010. Similarly, since the production trends for fodder corn and oats seem to project to zero before 2010, retaining production levels for these crops at 50% of current levels acknowledges that it is reasonable to expect these trends to continue and at the same time declares that it is equally reasonable to expect that production would not be entirely phased out in the short term. In this particular context, it can also be confirmed that the nature and purpose of this feasibility-level study are such that even a moderate degree of variance in the magnitude of crop requirement input parameters is not expected to substantially impact the overall results and/or conclusions.

Current and future crop production levels, without additional grain corn for ethanol, were determined with the methodology described in Table 5.8 for the separate OSL and CAS sub-regions of Eastern Ontario. For the regional minimum model-input requirements, the sums of the respective sub-regional production levels are utilized. According to the model specifications given in Section 5.3.2, the minimum sub-regional model-input requirements are set at 75% of the respective basic sub-regional levels. Where production data are insufficient to distinguish between separate OSL and CAS sub-regional production levels (e.g., for soybeans and winter wheat), it will be assumed that the ratio of production will be the same as the ratio of the respective acreage put to those crops during the 1996 census year for which county by county data are available. For winter wheat, the ratio is 30:70 for the OSL to CAS acreage and for soybeans, the OSL-CAS ratio is 90:10. Current crop production requirements determined with the above procedure for scenarios 1A and 1B, for all

of Eastern Ontario and for the separate OSL and CAS regions, are listed in Table 5.9. It will be assumed that all grain corn production requirements in scenario 1A are currently for non-ethanol uses. For scenario 1B, the respective grain corn production levels shown in Table 5.9 are those that would be required for other uses, **before** any subsequent additional demand for ethanol production is applied.

Table 5.9: Minimum Regional and Sub-regional Crop Production Requirements for Land Use Model -- Base Case and Maximum Grain Corn Production Scenarios.

Crop	Region	tonnes	tonnes
Grain Corn	All EO	578,950	
	OSL		400,538
	CAS		33,675
Fodder Corn	All EO	490,070	
	OSL		248,123
	CAS		119,430
Soybeans	All EO	108,800	
	OSL		73,440
	CAS		8,160
Hay	All EO	1,621,700	
	OSL		740,400
	CAS		475,880
Winter Wheat	All EO	5,900	
	OSL		1,328
	CAS		3,098
Oats	All EO	15,970	
	OSL		6,668
	CAS		5,310
Barley	All EO	93,400	
	OSL		49,560
	CAS		20,490
Mixed Grains	All EO	35,570	
	OSL		15,150
	CAS		11,528

Table 5.10: Minimum Regional and Sub-regional Crop Production Requirements for Agricultural Land Use Model – Status Quo Growth and Ethanol Development scenarios (excluding grain corn for ethanol).

Crop	Region	tonnes	tonnes
Grain Corn	All EO	709,000	
	OSL		498,038
	CAS		33,675
Fodder Corn	All EO	245,035	
	OSL		124,062
	CAS		59,715
Soybeans	All EO	163,200	
	OSL		110,160
	CAS		12,240
Hay	All EO	1,621,700	
	OSL		740,400
	CAS		475,880
Winter Wheat	All EO	5,900	
	OSL		1,328
	CAS		3,098
Oats	All EO	7,985	
	OSL		3,334
	CAS		2,655
Barley	All EO	93,400	
	OSL		49,560
	CAS		20,490
Mixed Grains	All EO	35,570	
	OSL		15,150
	CAS		11,528

The basic minimum regional and sub-regional crop production requirement inputs for the various future scenarios, without the additional requirements for grain corn for ethanol production included, are shown in Table 5.10. Where significant trends are evident in the recent production trends, it is assumed that such trends will continue to be expressed during the period 1996 through 2010. Changes from current production levels determined with the above methodology include decreases in fodder corn and oats and increases in soybeans and grain corn in the OSL Region only. For

the other four major crops and for grain corn in the CAS Region, the projected future requirements and applicable model inputs are maintained at current levels.

For scenarios 1B, 2B and 3A/B/C, additional grain corn production must be added to the base production levels listed in Tables 5.9 and 5.10. The extra grain corn requirements apply to the region as a whole because the model has no constraints stipulating that specific sub-regional production requirements must be met in this respect. Under scenarios 1B and 2B, the additional production requirements will be implemented in stages to examine the relationship between additional grain corn requirements and the total acreage allocated to all crops and up to the point where the limit on land availability is attained. Since potential future grain corn requirements represent ethanol production capacity, the relationship between ethanol demand increase as a percentage of total automotive fuel consumption and the total land area allocated to all crops in the respective scenarios can also be analyzed.

The additional grain corn requirements to be modeled in scenarios 1B and 2B will be added in steps of 200,000 tonnes per year until the limitation on land availability for crops is reached. In the Ethanol Development scenarios (3A/B/C), the specific grain corn requirements for the required ethanol production levels will be added to the overall crop production demands in a single, one-time increment.

Ethanol/Grain Corn Production Targets

The starting point for selecting ethanol and grain corn production targets for Scenario 3A is based on the 5% ethanol scenario proposed in the October 1998

Report “Canadian Solutions” by the David Suzuki Foundation/Pembina Institute for Appropriate Development (1998). In Section 5.3.3 it was stated that this strategy would require national ethanol production to be increased to 3,000 million litres per year or about five times the capacity expected to be available at the end of 2000 (Table 3.1). To scale this to the Eastern Ontario context, the population and fuel consumption projections shown in Table 5.11 are utilized.

Table 5.11: Population and Gasoline Consumption Projections.

Place	Population in 2010	Gasoline use in 2010
Canada	33.77 million*	36.9 billion litres*
Ontario	12.73 million*	–
Eastern Ontario	1.53 million**	1.67 billion litres**

* Source: Natural Resources Canada, 1997

** Population projection is based on the assumption that the proportion of its population to that of all Ontario will remain at about 12% as it was in 1996. Future gasoline requirements for Eastern Ontario were determined by assuming that the ratio of its requirements to that of all Canada would be the same as the ratio of its population to the Canadian population (0.0453).

The 5% ethanol penetration scenario (3A) for Eastern Ontario therefore yields an ethanol requirement in 2010 of 136 million litres per year. It is interesting to note that this target is expressly relevant to Eastern Ontario because it is approximately twice the 66 million litres per year design capacity of the Seaway Valley⁴⁴ ethanol-

⁴⁴ The Seaway Valley Farmer’s Energy Cooperative Inc.

for-fuel plant being constructed in Cornwall in 1999. In other words, about half the capacity suggested by scenario 3A is already being installed in Eastern Ontario⁴⁵.

The grain corn requirements in tonnes of production for the ethanol development scenarios are shown in Table 5.12. It is expected that the analysis to be performed with the land use model described in Section 5.3.2 will provide specific insight into the extent that grain corn production in Eastern Ontario could be increased to meet the various ethanol production targets.

Table 5.12: Ethanol Targets and Grain Corn Requirements for Eastern Ontario.

Future Ethanol Scenario	(% market penetration on an energy basis)	Ethanol production (million litres)	Corn required (tonnes) ⁴⁶	Corn required relative to 1996 EO production. ⁴⁷
2A	0	0	Base level	–
3A	5	136	348,700	0.51
3B	10	272	697,400	1.01
3C	30.5	829	2,125,600	3.1

⁴⁵ Recall from Section 5.3.3 that on a Canada-wide basis, the 5% ethanol penetration proposal would require approximately five times the national production capacity expected to be available by the end of 2000.

⁴⁶ At 390 litres per tonne as per the Commercial Alcohols Inc. plant in Chatham, Ontario.

⁴⁷ 687,900 tonnes as per the Ontario Ministry of Agriculture, Food and Rural Affairs Ontario Principal Field Crop Statistics for 1996 at www.gov.on.ca/OMAFRA.

Crop Rotation Factors

In Eastern Ontario, the continuous production of wide-row crops such as grain corn, fodder corn or soybeans is a potential threat to environmental quality because such crops are considered to be depleting crops as per the definition in Section 5.3.2. Hay or other grains (oats, barley and/or mixed grains) are typically grown in rotation with corn or soybeans to restore soil quality. Crop rotation requirements to be incorporated into the agricultural land use model are based on recommendations by the LEG (1984) and are summarized in Table 5.13. This table also shows the rotation coefficients for each land type for the respective constraint functions of the model. Because the replenishing crop types for corn (grain and/or fodder) and for soybeans on a particular land type are equal, the respective constraints can be expressed in a combined equation, for example: $(a_{\text{hay}} + a_{\text{grains}}) - (0.3333 a_{\text{corn}} + 0.5 a_{\text{soybeans}}) \geq 0$ on land types A and D ($t = 1,4$). This means that the environmental preservation requirements must be expressed in ten separate constraint functions – four for corn and soybeans on Land Types A and D in the two sub-regions of Eastern Ontario, four for corn only on Land Types C and E in the two sub-regions and two for corn and soybeans on Land Type B in the two sub-regions.

Table 5.13: Crop Rotation factors for Land Use Model.

Land Type	Depleting Crop(s)		Replenishing Crop(s)		k coefficient
	Crop Type(s)	Max. years	Crop Type(s)	Min. years	
A & D	Grain/Fodder Corn	3	Hay or Grains*	1	1/3
	Soybeans	2	Hay or Grains	1	1/2
B	Grain/Fodder Corn	2	Hay or Grains	2	1
	Soybeans	1	Hay or Grains	3	3
C & E	Grain/Fodder Corn	3	Hay or Grains	1	1/3
	Soybeans	NA	Hay or Grains	NA	NA

*Can be any or all of oats, barley or mixed grains.

Derived from Land Evaluation Group (1984).

6 ANALYSIS AND DISCUSSION

6.1 COMPARISON OF BASE CASE OUTPUT TO 1996 PRODUCTION DATA

The analysis and discussion of the potential for ethanol production in Eastern Ontario is divided into three sub-sections. Section 6.1 establishes the robustness of the model by comparing the output from the base case scenario to actual recent agricultural data for the region. Analyses of the land use implications of the various scenarios are presented in Section 6.2. These analyses are extended in Section 6.3 where the implications of the scenarios for ethanol production and greenhouse gas mitigation are discussed.

The agricultural land use model described in Section 5 is constructed in such a way that it integrates the essential elements of Eastern Ontario's agri-food sector. In conjunction with crop production requirements that are based on actual data, the model uses well-established estimates of the availability of land and associated yield factors as well as standard crop rotation specifications to determine the minimum level of land resources that would satisfy the constraints imposed on the system. Crop yield factors for each of the five land types have been updated from early 1980s estimates based on actual trends observed for the period between 1976 to 1981 and 1991 to 1996. In addition, the yield estimates included in the model match the current (average) observed data relatively well. Model output under base line conditions (Scenario 1A), in addition to serving as the basis or standard of comparison for output from the other scenarios, can therefore be expected to approximate current land use – including the overall minimum land requirement and the pattern, or distribution, of the major crop allocations – at an aggregate (regional)

scale and in a manner that is largely consistent with relevant census data.

Comparisons that are more specific are likely not warranted.

In this respect, there are two pertinent issues that are worth emphasizing: a) the applicability of comparing model output to census data vis-à-vis the nature of the model and b) the criteria to be used for evaluation, i.e., defining what the basis of comparison is. This model, like any other model, is but an abstraction and only a partial representation of reality. Two relevant characteristics of this model that will influence how appropriately “model solutions” represent reality include: a) many social and economic factors that are known to influence agricultural land use are absent and b) the particular bias of model’s objective function, because it provides a measure of land use potential by minimizing total land requirements, is not necessarily consistent with the driving forces behind typical farm-level decisions that will tend to impact actual land use patterns more directly. A consequence of these features is that calibration of the model is not feasible in a conventional meaning. These features however, do not detract from its utility in the current feasibility assessment as its structure and function are fully consistent with the objectives enumerated for the research component of this thesis.

As noted above, model output can be expected to approximate existing conditions at an aggregate, regional level under base line conditions. Specifically, one would expect the model to capture, in a relative sense, the overall distribution of agricultural land uses. In addition, with an objective function that attempts to minimize the overall requirements for agricultural land, it may be expected that the model will return a solution that allocates less land than what is actually reported for the period from which the base case data inputs were derived. The model is set up in such a

way that it will allocate crops by optimizing a number of production/productivity relationships to minimize the available resources. For example, crops with relatively higher productivity values will be preferentially allocated to land with better growth characteristics – if allowed under the constraints imposed on the system (i.e., all other things being equal). In actual practice, farm operators are not likely to employ the same degree of optimization – even if this were possible on an individual farm basis – with respect to land types and cropping choices. Furthermore, farm planning cannot be expected to take place at the regional scale. Lastly, the acreage of available land will tend to be greater than the seeded acreage because of losses at field margins and other possible less-than-optimal farm management practices. For the purposes of this research, presentation of the model output for the various scenarios will follow a consistent format of evaluating: a) the minimum regional land requirements and b) the aggregate (regional) land use patterns. The discussion on the results for each of the scenarios will generally be supported by data in summary tables and/or graphic formats that focus on the above two points of comparison while the actual (raw) model results are reported in an Appendix (B) to the thesis.

The base case output of the land use model results in a minimum regional land requirement of 407,300 hectares for the production of the major crops in Eastern Ontario (see printout provided in Table B1 of Appendix B for a sample of the model output). This value is 56% of the total land area cleared and available for agriculture (land types A through E), leaving an apparent reserve capacity of approximately 320 thousand hectares. This is comparable to the results of an earlier analysis (LEG, 1984) of the extent to which the region's agricultural production potential compared to estimates of its actual agricultural production in the early 1980s. Although the LEG (1984) model and that developed for this research exhibit some similarities and

some differences, both models indicate that there appears to be considerable potential to increase the level of production of agricultural commodities in Eastern Ontario. The models are similar in that they both evaluate the physical capacity of the same resource base and they both utilized the same kind of basic agricultural production parameters as input data for the same set of major crops. The models are different in that they have different objective functions, the prevailing yield factors and crop production requirements were somewhat different in the early 1980s compared to those in the mid-1990s and lastly, the LEG (1984) compared the maximum production potential to actual levels of production current in the early 1980s, not to a minimized regional land requirement. The LEG (1984) model showed that it was feasible to increase the amount of land under agricultural production by about 250 thousand hectares. Although the bases of comparison in the two models are not quite the same, the magnitude of the respective estimates of unused production potential is reasonably comparable, i.e., both models arrive at approximately similar conclusions with respect to the potential for agriculture in Eastern Ontario. The conformity of these results is used to confer additional validity to the model developed for this research.

Table 6.1 is a summary of the acreage allocated (absolute and relative) by the model to each crop. These are compared to the absolute and relative areas seeded to these crops in 1996 as reported by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA, 1996). Table 6.1 shows that the minimum regional land requirement, as allocated by the model to the major crops is similar to but somewhat less than (by 0.85 times) the total area seeded to these crops in 1996. This result is as expected for a land use model that is set to minimize the land use requirements for total agricultural production at the regional level.

Table 6.1: Summary of Base Case Model Allocations Compared to 1996 Seeded Areas.

	Grain Corn	Fodder Corn	Soybeans	Hay	Small Grains ⁴⁸	Total
Area Allocated by Model (ha)	84,034	20,795	45,352	205,597	51,526	407,304
% of Total Allocation	20.6	5.3	11.1	50.5	12.7	100
Area Seeded in 1996*	96,600	25,600	40,100	271,100	47,300	480,700
% of Total Seeded Area	20.1	5.3	8.3	56.4	9.8	100
Ratio of Total Allocation to Total Seeded Area (%).	87	81	113	76	109	85

* Source: OMAFRA Publication 20, 1996 (On-line <<http://www.gov.on.ca/OMAFRA/>>)

On a sub-regional basis, the proportions of minimum land requirements to total availability for the OSL and CAS sub-regions were 58% and 51% respectively (see Table B2 of Appendix B for details of base case output). Similarly, the ratio of land area allocated compared to the area seeded in 1996 was greater in the OSL Region than in the CAS Region (92% vs. 70%). Both these observations are consistent with the nature of the land use model. For most crops, the yield factors are higher in the OSL Region than in the CAS Region. Under most circumstances, the model is therefore expected to preferentially assign production to the OSL Region – if possible within the various constraints. A more in-depth analysis of the implications of sub-regional differences in model output is carried out for the Status Quo Growth scenario (Section 6.2).

⁴⁸ For the discussion of modeling results, the four cereal grain crops are lumped into a single category called "Small Grains".

Table 6.1 shows that the land allocations to three of the major regional crops (grain corn, fodder corn and hay) under base case conditions are also less than the respective areas seeded in 1996 – again, as expected for a model that seeks to minimize the total land area allocated to agricultural uses on a regional scale. These crops collectively account for the large majority (82%) of the area seeded in 1996 and the model allocated areas to these crops that were in the 76% to 87% range of the actual areas seeded. A good comparison between a) the areas allocated to each of these crops relative to the total area allocated and b) the areas seeded to these crops relative to the total area seeded in 1996 indicates that the model has captured the relative distribution or the pattern of the land resources sown to these major crops (i.e., the respective ratios are similar).

For soybeans and small grains, the model allocated somewhat more land than was seeded in 1996, which is initially counter-intuitive. Although the over-allocations are not overly out of line (about 13% and 9% respectively), a number of specific reasons underpinning these results may be enumerated. For soybeans, the following factors are relevant:

1. 1996 happened to be a year when the observed soybean productivity was somewhat higher than the recent average that was used to establish the respective yield factors employed by the model. Because the base case soybean production requirement input to the model was simply based on production data for the 1996 crop year (see Section 5.3.4 for rationale), this means that the actual seeded acreage could only be less than any allocation provided by the model. In other words, the expected smoothing effect of

averaging production requirements and crop yield factors was not applicable to the case of soybeans.

2. The origin of the crop yield estimates used in this model date back to the late 1970s/early 1980s when soybean production in Eastern Ontario was just being introduced. Because of the limited levels of production, from essentially zero production in 1976 to just less than 2,500 hectares under production in 1981, actual soybean yield factors for the region were likely not adequately characterized. As indicated in Section 5.3.4, yield estimates were marginally lower than observed values. This circumstance also has some carry over effect to the current yield estimates for soybeans.

The small grains (winter wheat, oats, barley and mixed grains) represent relatively less important crops in the region – together accounting for about 10% of the area seeded to crops in 1996. As a group, the model allocated a 9% greater acreage to the small grains than what was actually reported for 1996 (see Table B2 in Appendix B for the variations on an individual crop basis). These patterns are a consequence of the relatively small areas devoted to the small grains – smaller absolute differences will have larger relative differences – and because of the fact that for barley and mixed grains, the 1996 seeded areas were generally less than the average areas under production for the period 1991 through 1996 on which the production requirement inputs to the model were based (see Section 5.3.4 for the rationale for establishing the “current” levels of crop production requirements). Although the allocations for soybeans and small grains are opposite of what would normally be expected, the model still positions them reasonably well within the expected land use pattern of the regional agricultural system – the proportions of the acreage allocated

to the respective crops to the total allocation and of areas seeded relative to the total lands seeded are not too different from each other. In addition, they fit within the respective overall land use/allocation patterns. When all crops are considered, the rank order of prominence of the crops is the same in both the model allocation scheme and the actual land use pattern. In consideration of the above therefore, the variation between model results and the observations of actual acreage seeded to soybeans and small grains is not indicative of any fundamental deficiency of the agricultural land use model.

On the whole therefore, the land use model developed and implemented under baseline conditions for Eastern Ontario appears to adequately capture the major land use patterns at the regional scale. The minimum regional land requirement was close to, and as expected, slightly less than the total area under cultivation in 1996. The distribution of land resources allocated to the major crops also compare favorably with actual land use patterns observed in 1996 (the ratios are generally similar and the orders of crop prominence are similar). The model can therefore be used with good confidence for the feasibility assessments of the alternate scenarios.

6.2 SCENARIO ANALYSIS: LAND USE & CROP PRODUCTION ESTIMATES

6.2.1 MAXIMUM GRAIN CORN PRODUCTION (SCENARIO 1B)

Scenario 1B extends the base case scenario (1A) by incrementally increasing total grain corn production requirements beyond current levels in 200,000-tonne steps while maintaining all other conditions and requirements at baseline values. Output from the model under this scenario will provides an estimate of the maximum

potential for grain corn in Eastern Ontario. This theoretical “excess” production can then be converted into an ethanol-equivalent production capacity. As shown in Figure 6.1, the limit of available land (the line with solid circles for “All Crops”) under scenario 1B is reached when grain corn production approaches 1,325 thousand tonnes over and above the 579 thousand tonnes required for existing and conventional uses. This means that the maximum potential for grain corn is about 1,900 thousand tonnes in total. In other words, it appears that grain corn production levels in the region could technically be increased to as much as 3.3 times current levels, providing all other agricultural production parameters do not change. This assessment represents the maximum grain corn production potential, given full use of all available land in the region and the maintenance of current production levels for the other seven crops.

Figure 6.1 also shows how the land use distribution changes as the grain corn demand increases. It is readily evident that grain corn would occupy a progressively larger proportion of the land use distribution such that it would become the dominant land use (instead of hay) at about 900 thousand tonnes of extra production. Overall, the distribution of grain corn increases from about one-fifth to almost one half of the minimum regional land requirement while relative measures for the other major crops become steadily smaller. This indicates that a substantial shift in land use pattern would be needed to fully implement this scenario. See Table B3 in Appendix B for the detailed output of scenario 1B.

Figure 6.1: Minimum Regional Land Requirements (hectares) and Regional Land Use Patterns (percent of total allocation) vs. Grain Corn Demand - Scenario 1B

* Base Case Grain Corn Production Level is 578,950 tonnes for non-ethanol uses. In this scenario, the production requirements for the seven other crops are maintained at the respective base case levels.

6.2.2 STATUS QUO GROWTH SCENARIO (2A)

The Status Quo Growth scenario extrapolates existing crop production and yield trends into the near future as described in Section 5.3.3. To recap, the trends incorporated into the Status Quo Growth scenario included the following: crop yield factors for grain corn and soybeans were increased (in both sub-regions for both crops), production requirements were increased for grain corn in the OSL Region (still all non-ethanol demands) and for soybeans in both sub-regions. Production requirements were decreased in both sub-regions for oats and fodder corn.

Modeling output from scenario 2A is presented in Table B4 of Appendix B where it is compared to the output of the base case scenario. Figure 6.2 shows that the minimum regional (aggregate) land requirement for meeting all crop demands under the Status Quo Growth scenario is only slightly greater than the minimum land allocation of the base case output. The 419,629 hectares vs. 407,300 hectares represents a 3% increase in land resources allocated. This minimal degree of difference suggests that the trends incorporated into the Status Quo Growth scenario are consistent with expectations that large scale regional land use changes would not likely occur within a relatively short time frame. In the absence of an unusually strong external pressure (e.g., to produce large quantities of grain corn for the ethanol industry), it is expected that the area of land under production will remain relatively constant in the short term (see Section 4.3).

Because of the growth characteristics built into the Status Quo Growth scenario, some limited differences in the individual crop allocations (i.e. the specific regional

land use patterns) may be expected when compared to the corresponding patterns observed in the base case scenario. Figure 6.3 shows that the most notable differences in land use patterns between the base case scenario and those of the Status Quo Growth scenario are for the allocations of fodder corn (a

49% decrease) and for soybeans (a 36% increase). Differences between the land allocations of the other crops are relatively minor (see Table B4 in Appendix B).

The overall effect of these differences, there being some increases and some decreases, is that the near future potential for growing additional grain corn for the production of ethanol remains favorable under the Status Quo Growth scenario. It may therefore be expected as well, that the theoretical maximum regional grain corn production capacity under scenario 2B discussed subsequently will be similar to that expected for scenario 1B.

Status Quo Maximum Grain Corn Scenario (2B)

Scenario 2B extends the Status Quo Growth scenario (2A) by incrementally increasing total grain corn production requirements beyond current levels in

200,000-tonne steps while maintaining all other conditions and requirements at the respective Status Quo base line values. Figure 6.4 shows that under scenario 2B, the available land for crops is completely allocated when the added demand for grain corn approaches 1,420 thousand

tonnes. This potential maximum capacity is about 7% greater than that indicated for the maximizing grain corn scenario (1B). This means that the continuation of recent trends in crop yield improvements would only result in modest increases in the region's potential for corn-based ethanol production. The total potential maximum grain corn production under scenario 2B (at 2,129 tonnes per year) is 3.7 times the current regional production level and about 3 times above the production level established under the Status Quo Growth scenario.

The difference in regional land use patterns between scenarios 2A and 2B is shown in Figure 6.5. Not surprisingly, under scenario 2B, grain corn becomes the dominant land use; its share of the maximum regional land requirement is more than double the level under scenario 2A. The respective standings of the other major crops differ by between 55% and 72% of the respective Status Quo Growth base line values. This indicates that a substantial change in land use would have to be required to implement this scenario. See Table B5 in Appendix B for the detailed output from scenario 2B with 1,420 thousand tonnes extra grain corn.

Figure 6.4: Minimum Regional Land Requirement vs. Grain Corn Demand - Scenario 2B

* SQG Grain Corn Production Level is 709,000 tonnes for non-ethanol uses.

In this scenario, the production requirements for the seven other crops are maintained at the respective Status Quo Growth base line levels.

Earlier sections of this thesis have highlighted the different character of the two sub-regional units on which the analysis is based. In fact, the observed differences formed the rationale for treating Eastern Ontario as two distinct sub-regions in the agricultural land use model. Figure 6.4 shows that as the grain corn

demand increases under scenario 2B, the respective areas allocated by the model to all crops on a sub-regional basis follow different tracks to the respective levels of full allocation. It shows that for grain corn demand increases up to about 400 thousand tonnes, the amount of land that would be allocated to crops in the OSL Region does not change appreciably from the Status Quo Growth base level. On the other hand, the area that would be allocated in the CAS Region increases by about 40%.

Initially, it looks as though the OSL Region would not be playing as significant a role in producing additional grain corn as the CAS Region would under this scenario.

This seems somewhat counter-intuitive. Because most crop yield factors are slightly higher in the OSL Region than they are in the CAS Region, it might be presupposed that the model would allocate the land resources in the OSL Region in preference to those in the CAS Region as the demand for crop products increases. Beyond approximately 400 thousand tonnes and up to about 1,200 thousand tonnes of extra grain corn production, the pattern reverses with the minimum sub-regional land requirements in the CAS Region remaining quite constant while those of the OSL

Region increase. Above approximately 1,200 thousand tonnes, the point where the land area in the OSL Region is virtually 100% allocated, the trend again reverses until the available land in the CAS Region is also fully allocated.

Figure 6.6 shows the land areas allocated to all replenishing crops under the Status Quo Maximum Grain Corn scenario for the OSL and CAS sub-regions and for the region as a whole. Overall, the minimum regional land requirement increases gradually as the demand for additional grain corn increases. Although the model does not allocate more acreage to replenishing crops than that required to maintain the respective regional production demands, this acreage increase is a consequence of the design of the model in that it needs to allocate production of the replenishing crops to less productive land types as the grain corn demand increases. The sub-regional trends in replenishing crop land requirements appear to be mirror images of each other; as one increases, the other decreases and vice versa. Up to the point where additional demand for grain corn reaches 400,000 tonnes, the amount of land required for replenishing crops in the OSL Region decreases appreciably while it increases in the CAS Region by a corresponding amount. Close inspection of the model output at these levels shows that initially, as much as possible, the model shifts the production of replenishing crops – mostly hay and barley – from the OSL Region to the CAS Region and allocates grain corn production to roughly comparable areas in the OSL Region. This is a consequence of the fact the respective yield coefficients for grain corn are higher in the OSL Region than they are in the CAS Region. This means that the model will allocate grain corn to the OSL Region as long as possible under the various constraints imposed on it. After the maximum possible quantities of replenishing crops have been shifted out of the OSL Region – it is limited by the land preservation constraints and the minimum sub-regional production requirements

Figure 6.6: Grain Corn Land Requirements vs. Grain Corn Demand - Scenario 2B

* SQG Grain Corn Production Level is 709,000 tonnes for non-ethanol uses.

In this scenario, the production requirements for the seven other crops are maintained at the respective Status Quo Growth base line levels.

– the model allocates all extra grain corn production to the OSL Region, until all lands are allocated. These observations then provide the explanation why the earlier observations might initially seem to be inconsistent. Under this scenario therefore, the land required to produce increasingly greater quantities of grain corn (up to 400 thousand tonnes) would be allocated to the OSL Region while the requirement for replenishing crops would be shifted out of the OSL Region at a roughly comparable rate. This conjecture is confirmed in Figure 6.7 which shows that as grain corn production demands increase, the additional land allocated by the model is almost entirely accommodated in the OSL Region. This figure shows that the model does not begin to allocate substantially greater land requirements for grain corn in the CAS Region until the demand has increased beyond about 800 thousand tonnes per year.

Based on the above, it is concluded that both sub-regions could be important in the context of maximizing the potential contribution that the various ethanol penetration scenarios (e.g., scenarios 3A, 3B and/or 3C) may be able to make toward the objective of reducing greenhouse gas emissions on a regional basis by using ethanol as an automotive fuel.

6.2.3 ETHANOL DEVELOPMENT SCENARIOS (3A, 3B & 3C)

For the Ethanol Development Scenarios, the various specified levels of extra grain corn for ethanol were added to the basic Status Quo Growth scenario as outlined in the section on scenario specification. The model outputs are shown in Table B6 in Appendix B. This table also shows the proportions of the minimum regional land

Figure 6.7: Replenishing Crop Land Requirements vs. Grain Corn Demand - Scenario 2B

* SQG Grain Corn Production Level is 709,000 tonnes for non-ethanol uses.
In this scenario, the production requirements for the seven other crops are maintained at the respective Status Quo Growth base line levels.

requirement allocated for each scenario to the maximum available area and the minimum regional land requirement for each scenario relative to the Status Quo Growth baseline output.

Figure 6.8 shows that scenarios 3A and 3B are both clearly (technically) feasible in the context of the agricultural system of Eastern Ontario. Conversely, it is evident that the available agricultural land resources in Eastern Ontario cannot supply the demands imposed by scenario 3C. Specifically, the model could not generate a feasible solution that would meet all the regular demands for the major crops and supply sufficient grain corn to produce ethanol for an approximately 30% market penetration. Figure 6.8 also illustrates how the minimum regional land requirement for the major crops become a progressively larger proportion of the available land base with the increasing level of ethanol penetration implicit in the respective scenarios. The minimum regional land requirements for these scenarios would have to increase by 1.12 and 1.31 times the Status Quo Growth base level respectively, with larger proportions of the unused potential that would have to be brought into production in order to actualize the respective scenarios as the level of ethanol penetration increases.

Although the unused potential in scenario 3B is approximately 70% of that in scenario 3A, it is still a substantial reserve at one quarter of the available land base. Theoretically then, both scenarios 3A and 3B would appear to be capable of supporting ethanol production facilities to the extent specified for the respective scenarios.

Figure 6.9 shows the regional land use patterns associated with the ethanol development scenarios in comparison to that of the status quo growth base line scenario. It highlights the extent to which grain corn occupies larger proportions of the overall minimum regional land requirements

requisitioned by the various scenarios. Although the differences (increases) are readily apparent, and not insubstantial in absolute terms, there are no changes in the overall pattern. The sequential ranking of the crops does not change with grain corn remaining in second position. As with the level of ethanol penetration for scenarios 3A and 3B, they therefore represent a low to moderate level of land use change that would be required to realize the particular scenarios. To some extent, this too implies that scenarios 3A and 3B would appear to be inherently capable of supporting ethanol production facilities to the extent specified for these two scenarios.

6.2.4 MODIFIED GROWTH SCENARIOS

If an external pressure to produce ethanol at the level required by scenario 3C is brought to bear, it is expected that at some point, pressures to adjust other crop

requirements will kick in, if the system will allow.

Unfortunately, this analysis cannot provide further insight as to when or how the system would in fact respond in this kind of situation. However, an attempt was made to determine to what extent the crop production requirements

of Scenario 3C would have to be relaxed in order for the land use model to derive a feasible solution for the case where sufficient grain corn would be produced to support over eight hundred million litres of ethanol production. For this purpose, four modified growth scenarios were developed as described below. In the first case (Scenario 4A), it is judged that the demand for all crop requirements, other than grain corn for ethanol, could be reduced across the board to 75% of the respective Status Quo Growth scenario levels. For the second modified growth scenario (Scenario 4B), a crop-by-crop assessment of recent production data was made to further speculate on how specific production demand trends into the near future might be different from the basic 2A scenario. The rationale for the re-worked crop demands is described in the following.

Although the recent trends show increasing production levels grain corn and soybeans, for scenario 4B it is postulated that the production of these two crops could also be maintained at 1996 levels (the base case) for some time into the future. The trends for fodder corn (Figure B11a in Appendix A) in both sub-regions appear

to be approaching zero before the year 2010. In the Status Quo Growth scenario, it was assumed that actual production in the future would not decrease to less than one half of the 1991 to 1996 levels. For scenario 4B, it is assumed that fodder corn requirements could be further reduced to 25% of the base case level.

Figure B9a in Appendix A shows that hay production may be trending downward in the past eight to ten years, especially in the OSL Region. Whereas the Status Quo Growth scenario maintained hay production requirements at the base level because there was no strong trend overall, for scenario 4B, it is assumed that hay requirements could also decrease to 75% of the Status Quo Growth levels.

Of the four cereal grain crops, only oats showed definite decreasing production trends that were continued in the Status Quo Growth scenario. Although production requirements for the other three cereals were maintained at the base level in the Status Quo Growth scenario, most of the relevant trends may be interpreted to show more or less downward trends in the past ten years or so – except for barley production in the CAS Region where it appears to be holding steady or possibly rising slightly. For scenario 4B therefore, it is broadly postulated that production requirements for all four cereal crops could be reduced to 50% of the respective Status Quo Growth levels.

Scenario 4C is similar to scenario 2B, except that the sub-regional minimum production demands imposed on the system in all the other scenarios so far have been withdrawn. In other words, the constraint that was included to capture inertia in the agricultural production system was removed. Scenario 4D will be introduced if scenario 4C is not found feasible. It is similar to scenario 4C in all respects except that the demand for all crop requirements, other than grain corn for ethanol, would

be reduced across the board in increments of 5% until a feasible solution is found. All four modified growth scenarios are variants of scenario 3C in that the grain corn production requirement for ethanol is 2,126 thousand tonnes over and above that required for all other uses. The various input conditions for the modified growth scenarios and an indication as to whether they were found to be feasible are summarized in Table 6.2 below.

Table 6.2: Input Conditions for Modified Growth Scenarios

Scenario	Adjustments to Regional Production Requirements*	Inclusion of Minimum Sub-regional Production Requirements	Feasible Solution Found
4A	25% reduction from SQG levels to all crops.	yes	yes
4B	Reductions from SQG level vary by crop (see text).	yes	yes
4C	Same as SQG level.	no	no
4D	SQG level reduced in steps of 5% (all crops).	no	yes**

* Adjustments to regional production requirements for all crops except for the 2,126 thousand tonnes of grain corn for ethanol.

** Only when the overall regional production requirements were reduced to 75% of the Status Quo Growth levels.

The intention here is not to substantiate or to speculate on the validity of any of these modified growth scenarios. Rather, the purpose is firstly to identify whether there might be any feasible land use scenarios capable of supporting a 30% ethanol penetration objective. Secondly, it is considered helpful to gain initial insight into the kinds and levels of adjustments that would have to be made to future production requirements in order to realize the stated ethanol production goal.

The minimum regional land requirements derived from the model for the modified growth scenarios are shown in Figure 6.10. The detailed outputs for the modified growth scenarios are presented in Table B7 in Appendix B. It is interesting that both scenarios 4A and 4B yielded similar overall minimum regional land requirements. Moreover, both scenarios are shown marginally capable of meeting the ethanol production requirements for the 30% penetration target (i.e., they are just technically feasible). By definition (Section 5.3.3), the ethanol production level stipulated for these scenarios is capable of reducing greenhouse gas emissions in the automobiles and light trucks sector to levels that are 6% below their respective 1990 levels. In other words, if the agricultural system of Eastern Ontario could actually adjust to conditions as portrayed by either scenario 4A or 4B (i.e., if the technically feasible solutions are also found to be feasible from a number of other important perspectives), then ethanol could indeed be a very substantial component of a National Climate Change Strategy.

That scenario 4C is not feasible indicates that the constraints to maintain minimum sub-regional production requirements do not govern the determination of minimum regional land requirements in a major way. In fact, that it was necessary to reduce overall crop production requirements by 25% under scenario 4D before the model was able to generate a feasible solution indicates that these sub-regional production requirements do not appreciably affect the minimum regional land requirement. As shown in Figure 6.10, the minimum regional land requirement for scenario 4D is only 1.7 percentage points less than that of scenario 4A. In other words, scenarios 4A and 4D are very similar in terms of the overall land requirements for meeting the specified ethanol production objective. However, as is evident in Table B7 of Appendix B, the respective regional land use patterns are expected to be substantially

different between scenario 4A and scenario 4D. This then is confirmation that the rationale for including the constraints for the sub-regional minimum production requirements was not inappropriate. It appears that the agricultural system of Eastern Ontario can maintain any inertia with respect to existing land use patterns while simultaneously expanding the production of grain corn for an ethanol-for-fuel industry. The regional land use patterns of scenario 4D are therefore of little relevance in this analysis.

Regional land use patterns under the modified growth scenarios 4A and 4B are expected to be similar to the two maximizing grain corn production scenarios (1B or 2B) but with an even greater weighting to grain corn because of the reduced production requirements for the other crops (see Table B7 in Appendix B). In other words, these modified growth scenarios, which represent different theoretical maximum potentials for grain corn production in the region, imply that substantial shifts in land use would be required, both in terms of overall magnitude and in terms of compositional quality, if ever a decision was made to actually move toward implementation.

6.3 SCENARIO ANALYSIS: ETHANOL PRODUCTION AND GREENHOUSE GAS REDUCTION POTENTIALS

This section compares the projected ethanol production rates based on the theoretical maximum grain corn production rates indicated in the various modeling scenarios to estimated greenhouse gas emission reduction potentials. These are determined both in absolute terms (i.e., the actual quantity of greenhouse gas emissions that may be avoided) and in relative terms (i.e., the emission levels saved as a proportion of Eastern Ontario's share of the levels required to accomplish Canadian objectives inherent in the Kyoto Protocol.

In Section 3.3, it was noted that the greenhouse gas emission reduction benefit for ethanol is in the range of about 600 grams to 1,100 grams CO₂ equivalent per litre and in Section 2.6 it was observed that Canada's overall greenhouse gas emissions would have to decrease by 103 Megatonnes (Mt) per year in order to meet the national greenhouse gas reduction target as outlined in the Kyoto Protocol (1997). On a population proportional basis, Eastern Ontario's share of this target is about 4.67 Mt per year. Because greenhouse gas emissions from the automobiles and light trucks component of the transportation sector (i.e., vehicles that could utilize ethanol blend fuels) are about 15% of the country's overall emission, Eastern Ontario's share of the reductions required to meet the equivalent Kyoto Protocol target for the automobiles and light trucks sector is approximately 0.70 Megatonnes per year.

The ethanol and greenhouse gas emission reduction potentials (in terms of megatonnes CO₂ equivalent saved) of the modeled land use scenarios are summarized in Table 6.3. It shows that the potential greenhouse gas emission reductions are

substantial absolute quantities; from a minimum of 0.08 Mt to a maximum of 0.9 Mt CO₂ equivalent. Compared to the region's share of the national emissions reduction requirement to meet the Kyoto Protocol target, they are also significant reduction potentials⁴⁹. Even the minimum 2% contribution under scenario 3A is not inconsequential considering that it is the emissions reduction potential of a single strategy in one of several sectors.

Table 6.3: Ethanol and Greenhouse Gas Emission Reduction Potentials for Land Use Scenarios.

Scenario	Extra Grain Corn Demand*	Equivalent Ethanol Production	Potential GHG Reduction	Contribution to GHG Reduction to Meet Kyoto Targets (Overall)**
	thousand tonnes per year	million litres per year	Megatonnes CO ₂ eq. per year (range)	% (range)
1B	1,325	517	0.3 to 0.6	7 to 12
2B	1,420	554	0.3 to 0.6	7 to 13
3A	348.7	136	0.08 to 0.15	2 to 3
3B	697.4	272	0.16 to 0.3	3 to 6
3C	2,125.6	829	----- Not Applicable -----	
4A	2,125.6	829	0.5 to 0.9	11 to 20
4B	2,125.6	829	0.5 to 0.9	11 to 20
4C	2,125.6	829	----- Not Applicable -----	
4D	2,125.6	829	0.5 to 0.9	11 to 20

* This is over and above the grain corn required to satisfy non-ethanol demands.

** Relative to Eastern Ontario's share of the reduction targets for Canada as a whole.

Figure 6.11 clearly shows that the greenhouse gas emission reduction potentials are even more tangible and substantial for all feasible scenarios relative to Eastern Ontario's share of the reductions that would have to be realized in the automobile

⁴⁹ This assumes that all sectors and all regions should contribute proportionally to the overall goal of reducing emissions to 6% of their respective 1990 levels.

and light truck sector to satisfy Canadian targets inherent in the Kyoto Protocol. This figure shows that under the scenarios that represent minimal to modest ethanol penetration (3A/3B), potential greenhouse gas emission reduction benefits are about one quarter and one half respectively of the potential benefits indicated for the two maximizing grain

corn scenarios (1B and 2B). This means that technically, the region's apparent capacity to produce additional grain corn, and hence ethanol, could contribute substantially toward meeting Canada's Kyoto Protocol target.

Obviously, the ethanol penetration levels represented by scenarios 1B, 2B, 3A and 3B are not able to contribute the full amount required for this sector to comply with Kyoto Protocol expectations. However, as indicated in Section 2.6, ethanol as an alternate automotive fuel is but one of a number of possibilities in the transportation sector for reducing emissions. In this context then, even the 12% to 21% emission reduction benefits potentially offered by the minimal (5%) ethanol penetration scenario (3A) represent promising contributions to meeting the overall goal of reducing greenhouse gas emissions in Canada.

Because the ethanol production potentials of scenario 1B are about midway between those of scenarios 3A/3B and those of scenarios 4A/4B, they provide a convenient basis to evaluate the various potential ethanol requirements against the capacity of existing production facilities and/or overall national capacity. The additional 1,325 thousand tonnes of grain corn that could technically be produced would be a sufficient feedstock to maintain a hypothetical ethanol plant with an annual capacity of 517 million litres. This is a substantial volume of ethanol production – about eight times that of the plant being constructed by the Seaway Valley Farmer's Energy Cooperative Inc. in Cornwall, Ontario and about 3.5 times the capacity of the Commercial Alcohols Incorporated plant in Chatham, Ontario, which was the largest single ethanol production facility operating in Canada at the end of 1997. It also represents almost all (86%) of the total capacity expected to be available in all of Canada by the end of 2000 (see Section 3.2). This suggests that the Eastern Ontario land base could supply sufficient grain corn for several high-capacity ethanol plants.

A volumetric comparison shows that the 517 million litres of ethanol that could theoretically be produced from the excess grain corn production in Eastern Ontario is equal to about 1.5% of the total gasoline fuel currently used in Canada for automobiles and light trucks. On a population proportional basis – assuming that gasoline consumption in the region equals the average for the country as a whole – it would be about one third of the volume of gasoline currently consumed in Eastern Ontario. These comparisons also indicate that the production of ethanol from grain corn could become a substantial industrial enterprise in the region.

7 SUMMARY AND CONCLUSIONS

7.1 THESIS SUMMARY

7.1.1 OBJECTIVES AND METHODOLOGY

This thesis set out to examine the future prospects for a particular local option to mitigate greenhouse gas emissions as part of the battle against accelerated climate change on a global scale. In addition to the basic land use feasibility questions implicit in the purpose of the thesis, it has also been possible to confirm the extent to which the potential contribution is a substantial one and also to demonstrate what kind of scenarios might be representative of a future where ethanol contributes in this fashion. In order to answer the specific question concerning the extent to which Eastern Ontario could contribute to reducing greenhouse gas emissions by producing the grain corn needed to feed a substantial ethanol production industry, the research program was structured on three main objectives as follows.

Objective 1: To describe the nature and extent of the climate change problem.

It was shown (Section 2) that for the latter part of the 1990s, on a worldwide basis, anthropogenic greenhouse gas emissions were 6 billion tonnes to 7 billion tonnes of carbon annually. Canadian greenhouse gas emissions were 619 million tonnes carbon dioxide equivalent in 1995. Approximately 15% of Canada's greenhouse gas emissions originate from the use of fossil fuels in cars and light trucks.

Greenhouse gas emissions have been implicated as a contributing factor to the

climate change that is evident as a global warming trend during the twentieth century of about 1° C. Climate change, which includes many negative impacts such as coastal flooding, changing weather patterns (droughts, floods, severe storms, etc.) and the wider spread of tropical diseases, is expected to become more pronounced during the twenty-first century. The effect of large-scale mitigation measures, even if introduced successfully in the near term, may not be apparent for some hundreds of years hence.

Objective 2: To illustrate the potential role that ethanol might play in reducing greenhouse gas emissions (Section 3).

Ethanol contributes to greenhouse gas reductions because it is a renewable fuel, produced by the fermentation of plant biomass. Estimates of the benefit that ethanol produced from grain corn – the most likely source of large volumes of ethanol in eastern Canada – currently suggest that it can reduce emissions by about 30% to 60% relative to gasoline on an energy equivalent basis. By the end of 2000, Canada's ethanol production capacity is expected to be about 600 million litres per year. This is about 1.8%, by volume, of the projected gasoline consumption rate.

Objective 3: To determine Eastern Ontario's potential to support ethanol-for-fuel production by way of grain corn production and hence its ability to contribute to reducing greenhouse gas emissions (Sections 4 & 5).

A linear programming model was constructed and used to investigate the extent to which Eastern Ontario's available land resources could be utilized for both the

production of extra grain corn for ethanol and for the production of crops for all other existing and continuing demands. Development of the model consisted of these steps:

1. Identification of the guidelines according to which the model was developed as follows:

- The analysis would be restricted to Eastern Ontario.
- The regional agricultural system must continue to be able to supply existing needs.
- Because of the diversity evident across the region, it would be most appropriate to treat the region as two distinct sub-region; the OSL Region consisting of the counties Leeds & Grenville, Prescott & Russell, Stormont, Dundas & Glengarry and the Regional Municipality of Ottawa-Carleton and the CAS Region consisting of the counties Lennox & Addington, Lanark, Frontenac and Renfrew.
- The eight major crops (grain corn, fodder corn, soybeans, hay, winter wheat, oats, barley and mixed grains) would be considered as these typically account for more than 95% of the land used for crops in the region.

- Since land resources for crops in Eastern Ontario are finite, the model must not allocate crops to more land than what is available.
 - Because of the short term nature of the study, about 10 to 12 years under provisions in the 1997 Kyoto Protocol, no significant changes in land availability or in the inertia implicit in the present agricultural land use system would need to be incorporated into the model.
 - The nature of the analysis is a preliminary feasibility study. As such, it is evaluative, not prescriptive. The explicit treatment of economic parameters is beyond the scope of this study.
2. Establishing the appropriate structure of the model, including the specification of the units of analysis, the enumeration of the constraints imposed on the model and lastly, the selection of the objective function that was utilized to determine the minimum land allocations. The units of the analysis consisted of the individual land areas as allocated to each of the eight crops produced on each of the five land types in the two sub-regional geographic units. Constraints included provisions for the following:
- Overall minimum regional production requirements for all crop products must be met.
 - Minimal sub-regional production requirements must also be met.

- The total area of land allocated cannot exceed the amount of land that is available for the production of crops.
- Established crop rotation practices for each land type must be adhered to.

The objective function specified for the model specified that the sum of all areas allocated to the production of the eight major crops, on the five land types, and in both sub-regions must be the least amount possible.

3. Specification of various scenarios that described a range of possible futures where ethanol could contribute to greenhouse gas reductions. The basic scenarios were devised as follows:

- The base case to represent “current” conditions.
- The maximum grain corn production scenario represents the upper level of production that the system theoretically could produce under present circumstances.
- The Status Quo Growth scenario represents conditions as might be expected in the near future under the continuation of growth trends observed from the recent past.
- The future maximum grain corn production scenario represents the upper level of production that the system theoretically could produce in the near

future under the continuation of recent growth trends.

- Three specific ethanol production scenarios represent a range of its potential contribution to reducing greenhouse gas emissions – i.e., at minimal, modest and extensive levels. The respective ethanol penetrations into the motor fuel market under these scenarios were 5%, 10% and about 30% on an energy equivalent basis.

4. Identification and procurement of the relevant data that were needed for inputs to the model as follows:

- Estimates of the quantity of available agricultural land (hectares).
- Crop productivity factors (tonnes per hectare).
- Crop production requirements (tonnes).
- Coefficients to capture land preservation practices.

7.1.2 MAJOR FINDINGS

The preceding major section of the thesis has provided the results of the land use analysis on the various scenarios. The respective implications on overall land use requirements, on land use patterns and on the prospects for ethanol and greenhouse gas reductions were presented.

The base case output of the land use model showed that current regional crop requirements could theoretically be produced on 56% of the area estimated to be available for crops. This acreage projection compared reasonably well with the tally of land areas seeded to the major crops as reported in recent census documents, implying that the land use model adequately represented the agricultural system of the region. Under the Status Quo Growth scenario, the overall land requirements did not change appreciably from the base case scenario; in this case, 58% of the area available for crops was allocated to production. Only minor changes in land use patterns were observed with the Status Quo Growth scenario. These observations were consistent with the crop production trends built into the scenario in that no large-scale changes were forecast. As might be expected with the partial allocation of the available crop land, the apparent potential for the production of extra grain corn for ethanol under the base case and the Status Quo Growth scenarios is quite substantial – 1,325 thousand tonnes and 1,400 thousand tonnes respectively for the two scenarios.

For the ethanol development scenarios, only the first two were found to be feasible solutions. In these cases, the minimum regional land requirements increased to 64% and 75% respectively. Although the relative proportions of land areas allocated to the individual crops changed noticeably, the order of importance of the various crops in the 5% and the 10% ethanol penetration scenarios did not change from that shown for the Status Quo Growth scenario. In order to achieve the 30% ethanol penetration scenario, it was found that the demands for other crop products would have to be scaled back considerably. In one example, it was shown that the level of production for all non-ethanol-based crop requirements would have to be reduced to

75% of their respective Status Quo Growth levels in order to arrive at a feasible solution. Not only did the various modified growth scenarios examined result in an overall land use allocation that required virtually all of the available land resources for crops, substantial changes in land use patterns were also evident. For example, hay and grain corn changed places as the dominant crop in the region.

Based on the application of the linear programming model, there clearly appear to be a number of technically feasible solutions for grain corn production in Eastern Ontario that could satisfy the feedstock demands for large-scale ethanol production facilities. Overall, the various feasible scenarios are all able to support substantial volumes of ethanol production. For example, the 5% ethanol penetration scenario (the least aggressive of all scenarios evaluated) appears capable of supporting an ethanol plant with a capacity of 136 million litres per year. By way of comparison, the Seaway Valley Farmer's Energy Cooperative Inc. plant expected to be constructed in Cornwall, Ontario in 1999 has a design capacity of 66 million litres ethanol per year. Under the two maximum grain corn production scenarios (1B and 2B), theoretical grain corn production levels could feed ethanol plants with a combined capacity of approximately 500 million litres to 550 million litres per year. Under scenarios where other food crop production demands are reduced (i.e., to meet the requirements of the 30% ethanol penetration scenario), ethanol production in excess of 800 million litres per year could be achieved.

With the production and use of ethanol in quantities as noted above, substantial reductions in the emission of greenhouse gases could be attained. The analysis has shown that absolute reductions in the order of 0.08 Mt to 0.9 Mt annually may be

possible and that these are substantial in the context of the greenhouse gas emission reductions required to help Canada meet its Kyoto Protocol commitments. These reductions are between 2% and 20% of the region's share of the overall greenhouse gas reduction requirements needed to bring emissions back to a level that is 6% below comparable 1990 levels. Furthermore, these potential reductions constitute 12% to 130% of the reductions required to bring emissions from the automobiles and light trucks sector from projected year 2000 levels to the 6% of 1990 levels. Since ethanol is but one potential emission reduction strategy applicable to the transportation sector, and because emission reductions can be expected as a result of strategies in other sectors as well, these potential contributions from ethanol may be considered impressive. For example, under certain circumstances, such as some of the modified growth scenarios, the use of ethanol as an alternative transportation fuel appears fully capable of contributing the entire emission reduction quota assumed for the transportation sector.

In this respect, it is concluded that the overall objectives set out for this research endeavor have certainly been accomplished. The analysis has shown that it is technically feasible to substantially increase the level of grain corn production in Eastern Ontario in support of a major ethanol-for-fuel industry – the available agricultural land resources in the region appear to be capable of accommodating significant production increases. Given the range of possibilities, the implied level of ethanol production has the potential to contribute meaningfully to national efforts aimed at reducing greenhouse gas emissions and hence mitigating the negative impacts of climate change. Lastly, there appear to be a number of plausible scenarios under which such contributions could be realized.

7.2 ADVANCING THE RESEARCH

As indicated at the outset, the analysis presented herein constitutes an important and a preliminary step in the larger overall process of determining the extent to which ethanol actually can be, or ought to be, part of Canada's strategy for reducing greenhouse gas emissions. It is therefore appropriate to briefly consider the kinds of additional research and/or assessments that would have to be done as a follow up to this work and as a possible precursor to developing national policies to address the very pressing issue of climate change.

Whereas the technically feasible agricultural solutions identified in this analysis span a range of ethanol penetration scenarios that have increasingly impressive greenhouse gas reduction benefits, it also becomes increasingly difficult to speculate with respect to the prospects for actually establishing a regional ethanol-for-fuel industry at a scale indicated by any of these scenarios. A summary of the modeling output (Table 7.1) clearly shows that as the level of ethanol penetration increases, the extent to which the regional vehicle mix must include a greater proportion of E85 vehicles, the required increase in installed ethanol production capacity and the relative volume of conventional gasoline sales which would be displaced all become increasingly substantial as well. Furthermore, uncertainties with respect to various functional properties of the regional agricultural system, such as the following examples, are also expected to have an impact on whether a particular ethanol scenario would ultimately be proposed for implementation.

Table 7.1: Summary of Output from Agricultural Land Use Model for Status Quo Growth (SQG), Ethanol Development and Modified Growth Scenarios.

Scenario	Vehicle Mix Required to Realize Scenario (%)			Volume of Conventional Fuel Sales Displaced (%)	Ethanol Production Capacity Increase Required	Percent of Available Land Allocated by Model (%)	Greenhouse Gas Emission Reductions Relative to Region's Share of Respective Requirements	
	Conventional Fuel Vehicles	E10 Vehicles	E85 Vehicles				All GHG Emissions (%)	Emissions from Cars and Light Trucks (%)
SQG (2A)	-	-	-	0	-	58*	-	-
5% Penetration (3A)	20	80	0	8	5×	64	2 to 3	12 to 21
10% Penetration (3B)	2	90	8	16	10×	75	3 to 6	23 to 43
Max Grain Corn Under SQG (2B)***	0	85	15	30	20×	100	7 to 13	47 to 87
30% Penetration (3C)	0	50	50	50	30×	Not Feasible	Not Applicable	Not Applicable
30% Penetration (4A, B & D)	0	50	50	50	30×	93 to 96**	11 to 20	71 to 130

* Amount required for all non-ethanol crop demands.

** Can only be achieved if demands for other crop products are substantially reduced from the base SQG scenario (see text for explanation).

*** This is very close to a 20% ethanol energy penetration scenario.

The ability of Eastern Ontario's grain corn "industry" to adapt to major changes in demand with reasonable timeliness is one important, and likely unknown aspect of the system that will determine its ultimate potential ethanol production capacity. The total land areas allocated to the production of grain corn (all uses) under the ethanol development and the feasible modified growth scenarios are shown in Table 7.2 below. Relative to the Status Quo Growth scenario, the required acreage increases by about one half in scenario 3A, it more than doubles in scenario 3B and it approaches a 5× increase in scenarios 4A and 4B – all very substantial increases.

Table 7.2: Areas Allocated to Grain Corn by Land Use Model.

Scenario	Allocated Acreage	
	Hectares	Relative to SQG
Status Quo Growth	89,270	1.0
3A	133,097	1.48
3B	200,148	2.23
3C	Not Applicable	Not Applicable
4A	412,026	4.56
4B	417,471	4.65

Similarly, the extent to which non-ethanol crop production requirements could be reduced to make room for additional grain corn production, especially in the case of the modified growth scenarios, is likely not well known. This relates on the one hand to the overall desirability of implementing a particular solution derived by the land use model (i.e., it is a policy issue) and to maintaining a sustainable level of dependence on the land base in the region for adequate supplies of other agricultural products on the other. In addition, issues such as the practicability of substantially relying on or utilizing land with marginally adequate crop production capabilities (e.g., land type E)

and uncertainties with respect to the currently available agricultural land resources in the region, etc., may also be expected to have some impact on the ultimate extent to which ethanol solutions could be implemented.

In order to more clearly define the specific contribution that ethanol in Eastern Ontario would be able to make toward reducing greenhouse gas emissions, and hence its role in Canada's National Climate Change Strategy, it is necessary to first investigate/resolve the above and other related issues as listed below. This is not intended to be an exhaustive, or a particularly detailed enumeration, but an initial sampling that is illustrative of the multi-faceted nature of the anticipated overall assessment process for identifying and bringing an ethanol scenario to fruition. In addition, the identification of potential follow-up research and/or assessment also serves as an indicator of the proper context for the role that this study was able to contribute to that process.

Potential additional inputs required to support a decision in favor of an ethanol-based strategy for greenhouse gas mitigation are presented according to three levels of involvement. The first level consists of additional work within the specific context of producing grain corn in Eastern Ontario for ethanol. In this respect, the following suggestions may be seen as possible ways that the specific research in this thesis could be enhanced or expanded.

- An undertaking to map out and describe the overall assessment process and to identify all the requisite components and their inter-relationships, both internal and external to the ethanol option, could be beneficial. Although it is appropriate

to conduct a feasibility-level assessment (i.e., this study) independent of a broader coordinated assessment framework – because it is one of the earliest requirements – other major studies could be better pursued within the larger overall context.

- An essential and relatively immediate possibility for follow-up would be to conduct a comprehensive and detailed agro-economic assessment. This could include, among other things, a study to identify, classify and attempt to quantify all the market-related and other issues applicable to the agricultural economy, and especially, to the grain corn industry of the region.
- A research program to up-date the LEG (1984) estimates of the amount of land available for crops and/or to independently corroborate the current availability of these resources within the region would be a valuable contribution to confirming the validity and accuracy of the upper limits projected for grain corn production in this study. There is at present no practicable basis on which to judge the degree of uncertainty associated with these land availability estimates. Although the estimates are not expected to be seriously deficient, the actual variance may be sizable enough to noticeably affect the ultimate maximum grain corn production capability of the region. A re-visiting and updating of the LEG (1984) process, in conjunction with the utilization and analysis of applicable remote sensing data could therefore be initiated and potentially lead to the development of a comprehensive GIS database of the agricultural resources in Eastern Ontario that would be especially beneficial in the context of planning and/or implementing ethanol scenarios.

- The land use model developed for this thesis used crop yield values that had their origin in estimates derived from a general crop model. A study to investigate the range of actual yields experienced throughout the region as a function of land type (i.e., lands with different bio-physical qualities) could therefore lead to refinements in the grain corn projections for the various ethanol scenarios. Although such new information could be useful, is not considered essential because variations are expected to be minor in comparison to the magnitude of the maximum potential grain corn production.

The second level of follow-up research/assessment would consist of work related to the production and use of ethanol in general and could include items such as:

- A detailed technical assessment of the potential for introducing E85 vehicles in Canada in the near future.
- An impact assessment of the ethanol strategy on the established petroleum-based motor fuel industry.
- Research into the consumer acceptability of any specific proposals for enhanced ethanol penetration into the market place.
- Detailed technical, financial and planning studies to determine the technical/commercial viability of establishing the infrastructure for the prescribed ethanol production requirements.

- Studies to identify potentially viable corn-based ethanol futures with the anticipation that alternate feedstocks and processes become available for ethanol production on a large scale (e.g., ligno-cellulose)

The final level of further research and/or assessment that would likely be required in the context of discerning whether an ethanol-based climate solution should be pursued focuses on issues specific to national efforts to reduce greenhouse gas emissions from all sources. These may include:

- A comprehensive evaluation and impact assessment of the full range of feasible greenhouse gas mitigation options identified through the national climate change process. This could include cost/benefit analyses of ethanol-based solutions with respect to other promising strategies.
- Continued fuel cycle modeling studies to refine and/or standardize the estimate of ethanol's greenhouse gas reduction benefit.

As a final comment, it is important to again be reminded that the model results presented herein are evaluative of basic feasibility; they ought not to be considered or used as a prescription for optimal land use. Although it was shown that on a preliminary basis, there is potential for using the available land resources to meet substantially increased future agricultural demands, including non-food demands, the results cannot dictate how the agricultural resources in any part of Eastern Ontario ought to be used. On the other hand, if it is decided that ethanol ought to become the contributor to greenhouse gas reduction that it now appears to be capable of

being, regional, provincial and/or federal authorities must be made aware that Eastern Ontario has significant potential in this regard and that the region ought to be considered for development as a major ethanol supplying region. Further technical analyses and more detailed studies, including socio-economic and environmental assessments, can then be initiated. Because the prospects for climate change and its various possible negative consequences for humanity do not appear to be improving rapidly, and because it is the duty of all societies to exercise proper steward-like management of the earth's natural resources, the current conclusions can therefore be considered an important first step in a process which ought to be explored further with urgency and due diligence.

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Appendix A

Agricultural Trends in Eastern Ontario - 1976 through 1996

Figure A1
Total Land Area on Census Farms in Eastern Ontario

Source: Statistics Canada

Figure A2
Improved Land on Census Farms in Eastern Ontario

Source: Statistics Canada

Figure A3
Area of Cropland on Census Farms in Eastern Ontario

Source: Statistics Canada

Figure A4
Unimproved Land Area on Census Farms in Eastern Ontario

Source: Statistics Canada

Figure A5a: Winter Wheat Production in Eastern Ontario

Trend is not statistically significant.

Figure A5b: Winter Wheat Yields in Eastern Ontario

Source: OMAFRA Publication 20, 1976 through 1996.

Figure A6a: Production of Oats in Eastern Ontario

Both trends statistically significant.

Figure A6b: Yield of Oats in Eastern Ontario

No statistically significant difference between CAS and OSL Region Yields.

Source: OMAFRA Publication 20, 1976 through 1996.

Figure A7a: Barley Production in Eastern Ontario

Figure A7b: Barley Yields in Eastern Ontario

No differences between OSL and CAS Region yields.

Source: OMAFRA Publication 20, 1976 through 1996.

Figure A8a: Mixed Grain Production in Eastern Ontario

Figure A8b: Mixed Grain Productivity in Eastern Ontario

No significant differences between OSL and CAS Region yields.

Source: OMAFRA Publication 20, 1976 through 1996.

Figure A9a: Hay Production in Eastern Ontario

Figure A9b: Hay Yields in Eastern Ontario

Difference between yields in OSL and CAS Regions is significant.

Source: OMAFRA Publication 20, 1976 through 1996.

Figure A10a: Grain Corn Production in Eastern Ontario

Trend in CAS Region is statistically significant.

Figure A10b: Grain Corn Yields in Eastern Ontario

Trends are statistically significant.

Difference between CAS and OSL Regions is significant at 95% CL.

Source: OMAFRA Publication 20, 1976 through 1996.

Figure A11a: Fodder Corn Production in Eastern Ontario

Both trends statistically significant.

Figure A11b: Fodder Corn Yields in Eastern Ontario

No significant trends or differences.

Source: OMAFRA Publication 20, 1976 through 1996.

Figure A12a: Soybean Production in Eastern Ontario

Non-linear trend.

Figure A12b: Soybean Yields in Eastern Ontario

Trend is statistically significant.

Source: OMAFRA Publication 20, 1978 through 1996.

Appendix B

Detailed Land Use Model Outputs

Explanatory Notes:

Table B1 is a printout of the spreadsheet of the Land Use Model under the Base Case scenario. There is a row for each constraint function and one column for each decision variable (x1 to x80). Column headings for the decision variables show the three functional units of the analysis expressed in the order: Geographic sub-region (here East = the OSL sub-region and West = the CAS sub-region), Land Type, Major Crop. The row titled “Variable values” contains the resultant (model output) values for the decision variables.

The spreadsheet matrix contains all of the objective function coefficients. These are presented in four main blocks as follows:

1. Land availability limits.
2. Regional production requirements.
3. Sub-regional production requirements.
4. Crop rotation factors.

The Right Hand Side (RHS) values for each constraint function appear in the last column of the outlined grid and the actual model solution values are found in the “Optimal Solution” column.

Table B1 continued.

West, E, Mixed Grains		Optimal Solution	RHS Values	
x80				
0				
1	=	407,304		
	<=	114,000	114,000	hectares A
	<=	33,274	50,000	hectares B
	<=	114,000	114,000	hectares C
	<=	38,000	38,000	hectares D
	<=	0	203,000	hectares E
	<=	60,000	60,000	hectares A
	<=	14,106	33,000	hectares B
	<=	26,923	58,000	hectares C
	<=	7,000	7,000	hectares D
1	<=	0	52,000	hectares E
	>=	578,950	578,950	tonnes Grain Corn
	>=	490,070	490,070	tonnes Fodder Corn
	>=	108,800	108,800	tonnes Soybeans
	>=	1,621,700	1,621,700	tonnes Hay
	>=	5,900	5,900	tonnes Winter Wheat
	>=	15,970	15,970	tonnes Oats
	>=	93,400	93,400	tonnes Barley
0.8	>=	35,570	35,570	tonnes Mixed Grains
	>=	545,275	400,538	tonnes Grain Corn
	>=	248,123	248,123	tonnes Fodder Corn
	>=	73,440	73,440	tonnes Soybeans
	>=	1,145,820	740,400	tonnes Hay
	>=	2,802	1,328	tonnes Winter Wheat
	>=	10,660	6,668	tonnes Oats
	>=	72,910	49,560	tonnes Barley
	>=	24,042	15,150	tonnes Mixed Grains
	>=	33,675	33,675	tonnes Grain Corn
	>=	241,947	119,430	tonnes Fodder Corn
	>=	35,360	8,160	tonnes Soybeans
	>=	475,880	475,880	tonnes Hay
	>=	3,098	3,098	tonnes Winter Wheat
	>=	5,310	5,310	tonnes Oats
	>=	20,490	20,490	tonnes Barley
0.8	>=	11,528	11,528	tonnes Mixed Grains
	>=	68,081	0	A
	>=	25,113	0	B
	>=	-	0	C
	>=	38,000	0	D
	>=	0	0	E
	>=	37,891	0	A
	>=	13,156	0	B
	>=	6,019	0	C
	>=	7,000	0	D
1	>=	0	0	E

Table B2: Detailed Model Output - Base Case (1A).
Allocated Areas (hectares)

Region	Grain Corn	Fodder Corn	Soybeans	Hay	W. Wheat	Oats	Barley	Mix Grains	Sml Grains*	Sum
OSL	78,387	10,763	30,613	142,091	860	3,925	24,167	8,468	37,419	299,274
CAS	5,646	10,032	14,740	63,506	950	1,982	6,970	4,204	14,106	108,030
Total	84,034	20,795	45,352	205,597	1,810	5,907	31,137	12,671	51,526	407,304
% of allocated land	20.6	5.1	11.1	50.5	0.4	1.5	7.6	3.1	12.7	100
Areas seeded in 1996**										
OSL	88,500	17,160	36,180	156,950	770	5,260	15,860	5,540	27,430	326,220
CAS	8,130	8,400	3,880	114,160	1,840	4,170	9,310	4,570	19,890	154,460
Total	96,600	25,600	40,100	271,100	2,600	9,400	25,200	10,100	47,300	480,700
% of seeded land	20.1	5.3	8.3	56.4	0.5	2.0	5.2	2.1	9.8	100
Ratio of Allocated/Seeded										
OSL										0.92
CAS										0.70
Total	0.87	0.81	1.13	0.76	0.70	0.63	1.24	1.25	1.09	0.85

* This is the sum of Winter Wheat, Oats, Barley and Mixed Grains.

** Source: OMAFRA Publication 20, 1996 (On-line <<http://www.gov.on.ca/OMAFRA/>>).

Table B3: Detailed Model Output - Maximum Grain Corn Production (1B) with 1,325 thousand Tonnes Extra Grain Corn.
Allocated Areas (hectares)

Region	Grain Corn	Fodder Corn	Soybeans	Hay	W. Wheat	Oats	Barley	Mix Grains	Sml Grains*	Sum
OSL	304,113	9,522	30,613	149,548	407	2,455	16,428	5,914	25,204	519,000
CAS	48,650	10,648	14,740	107,497	1,402	3,473	14,913	6,848	26,636	208,171
Total	352,763	20,171	45,352	257,046	1,810	5,928	31,340	12,761	51,840	727,171
% of allocated land	48.5	2.8	6.2	35.3	0.2	0.8	4.3	1.8	7.1	100.0

Table B4: Detailed Model Output - Status Quo Growth Scenario (2A)
Allocated Areas (hectares)

Region	Gr. Corn	Fodder Corn	Soybeans	Hay	W. Wheat	Oats	Barley	Mix Grains	Sml Grains*	Sum
OSL	84,553	5,542	41,711	138,789	860	1,962	24,167	8,468	35,457	306,052
CAS	5,167	5,016	20,083	70,195	950	991	6,970	4,204	13,115	113,577
Total	89,720	10,558	61,795	208,984	1,810	2,954	31,137	12,671	48,572	419,629
% of allocated land	21.4	2.5	14.7	49.8	0.4	0.7	7.4	3.0	11.6	100.0
Base Case Output (1A)										
OSL	78,387	10,763	30,613	142,091	860	3,925	24,167	8,468	37,419	299,274
CAS	5,646	10,032	14,740	63,506	950	1,982	6,970	4,204	14,106	108,030
Total	84,034	20,795	45,352	205,597	1,810	5,907	31,137	12,671	51,526	407,304
% of allocated land	20.6	5.1	11.1	50.5	0.4	1.5	7.6	3.1	12.7	100.0
2A minus 1A	5,686	(10,237)	16,442	3,387	-	(2,954)	-	-	(2,954)	12,325
% change	6.8	(49.2)	36.3	1.6	-	(50.0)	-	-	(5.7)	3.0

* This is the sum of Winter Wheat, Oats, Barley and Mixed Grains.

Table B5: Detailed Model Output - Status Quo Maximum Grain Corn Scenario (2B) with 1,420 thousand Tonnes Extra Grain Corn.
Allocated Areas (hectares)

Region	Grain Corn	Fodder Corn	Soybeans	Hay	W. Wheat	Oats	Barley	Mix Grains	Sml Grains*	Sum
OSL	299,945	4,761	41,711	147,379	407	1,227	16,428	7,141	25,204	519,000
CAS	47,547	5,324	20,083	112,464	1,402	1,736	14,913	5,577	23,629	209,048
Total	347,492	10,085	61,795	259,843	1,810	2,964	31,340	12,718	48,832	728,048
% of allocated land	47.7	1.4	8.5	35.7	0.2	0.4	4.3	1.7	6.7	100.0

Table B6: Detailed Model Output - Ethanol Development Scenarios (3A & 3B).
Allocated Areas (hectares)

Region	Grain Corn	Fodder Corn	Soybeans	Hay	Winter Wheat	Oats	Barley	Mixed Grains	Small Grains*	Sum	% of available land
OSL	127,930	4,761	41,711	116,393	407	1,227	16,428	7,141	25,204	316,000	61
CAS	5,167	5,212	20,083	97,928	1,402	1,736	14,913	5,577	23,629	152,020	72
Total	133,097	9,974	61,795	214,322	1,810	2,964	31,340	12,718	48,832	468,020	64
% of alloc'd land	28.4	2.1	13.2	45.8	0.4	0.6	6.7	2.7	10.4	100	
Relative to SQG	1.48	0.94	1.00	1.03	1.00	1.00	1.01	1.00	1.01	1.12	
OSL	194,733	4,761	41,711	123,495	407	1,227	16,428	7,141	25,204	389,904	75
CAS	5,415	5,324	20,083	103,549	1,402	1,736	14,913	5,577	23,629	158,000	75
Total	200,148	10,085	61,795	227,044	1,810	2,964	31,340	12,718	48,832	547,904	75
% of alloc'd land	36.5	1.8	11.3	41.4	0.3	0.5	5.7	2.3	8.9	100	
Relative to SQG	2.23	0.96	1.00	1.09	1.00	1.00	1.01	1.00	1.01	1.31	

* This is the sum of Winter Wheat, Oats, Barley and Mixed Grains.

Table B7: Detailed Model Output - Modified Growth Scenarios (4A, 4B & 4C).

4A Allocated Areas (hectares)										
Region	Grain Corn	Fodder Corn	Soybeans	Hay	Winter Wheat	Oats	Barley	Mixed Grains	Small Grains*	Sum
OSL	337,832	3,571	31,284	126,739	306	921	12,321	6,028	19,575	519,000
CAS	74,194	3,395	15,062	74,323	1,052	1,302	11,185	3,487	17,026	184,000
Total	412,026	6,966	46,346	201,061	1,357	2,223	23,505	9,515	36,600	703,000
% of alloc'd land	58.6	1.0	6.6	28.6	0.2	0.3	3.3	1.4	5.2	100
4B										
Region										
OSL	342,984	2,381	27,808	134,129	204	614	8,214	2,668	11,699	519,000
CAS	74,488	2,263	13,389	58,474	701	868	7,456	3,723	12,749	161,363
Total	417,471	4,644	41,197	192,603	905	1,482	15,670	6,391	24,448	680,363
% of alloc'd land	61.4	0.7	6.1	28.3	0.1	0.2	2.3	0.9	3.6	100
4D										
Region										
OSL	356,560	0	6,346	136,716	0	0	9,981	9,396	19,377	519,000
CAS	51,233	8,088	40,000	54,975	1,357	2,236	13,585	0	17,179	171,475
Total	407,793	8,088	46,346	191,692	1,357	2,236	23,567	9,396	36,556	690,475
% of alloc'd land	59.1	1.2	6.7	27.8	0.2	0.3	3.4	1.4	5.3	100
2B										
Region										
OSL	299,945	4,761	41,711	147,379	407	1,227	16,428	7,141	25,204	519,000
CAS	47,547	5,324	20,083	112,464	1,402	1,736	14,913	5,577	23,629	209,048
Total	347,492	10,085	61,795	259,843	1,810	2,964	31,340	12,718	48,832	728,048
% of alloc'd land	47.7	1.4	8.5	35.7	0.2	0.4	4.3	1.7	6.7	100

* This is the sum of Winter Wheat, Oats, Barley and Mixed Grains