Cost Effective Greenhouse Gas Mitigation in the Ontario Dairy Sector

by

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ABSTRACT

COST EFFECTIVE GREENHOUSE GAS MITIGATION IN THE ONTARIO DAIRY SECTOR

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This study determines the feeding practices that can reduce greenhouse gas (GHG) emissions from milk production in Ontario at least cost, and estimates the associated impact on farm gross margin.

A linear programming model is developed to account for emissions both from the farm as well as from the production of feed and other inputs upstream. The results indicate that changing rations can reduce GHG emissions from milk production by up to 35% from original levels, with a corresponding decline in farm gross margin of 23.4%. The cause of the declines in GHG emissions is because corn silage is replaced by high quality perennial forage (alfalfa hay). This allows for an increase in carbon storage in land, due to the enhanced carbon storage capacity of perennial forages as opposed to annual crops (i.e. corn), and due to lower capital and chemical inputs. The implications are that there is large potential for reducing GHG emissions from milk production in Ontario due to the potential for perennial forages to capture and store carbon in soil. This necessitates that perennial forages replace corn silage as the primary source of roughage in dairy rations. Current rations have corn silage as about 20% of dry matter intake.

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TABLE OF CONTENTS

Page

List of Tables

List of Figures

Chapter 1

Introduction

1.0 Introduction

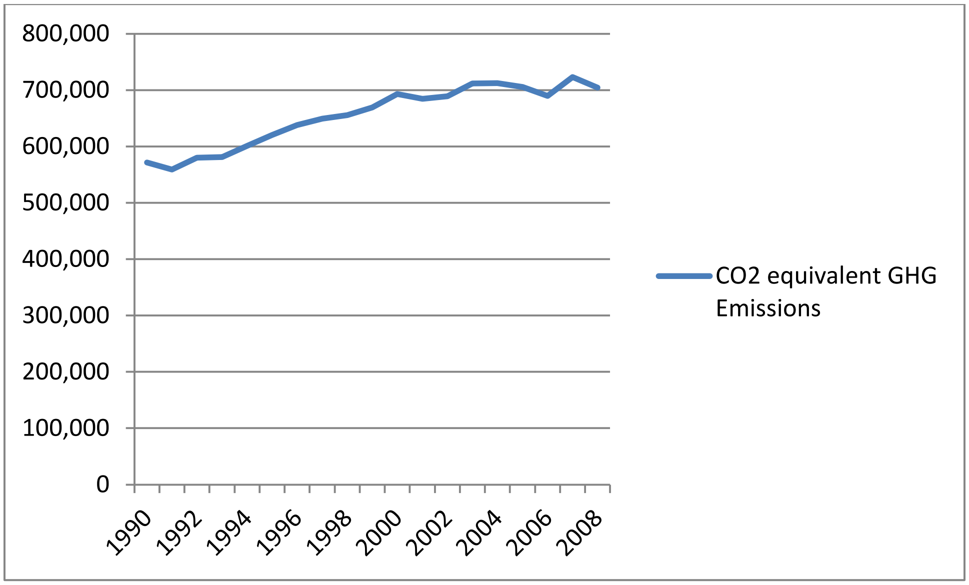
Growing evidence linking greenhouse gases (GHGs) to rises in global temperatures and climate change is leading to efforts to determine low cost methods of GHG mitigation. Figure 1.1 shows that total Canadian CO_2eq (carbon dioxide equivalent) GHG emissions have been increasing throughout the period 1990-2008. Emissions begin at below 600,000 kt (kilotonnes) in 1990 and end at above 700,000 kt in 2008. Figure 1.2 shows that CO_2eq GHG emissions from agricultural production have also been increasing in the period 1990-2008. Emissions from this source begin at below 60,000 kt in 1990 and end at above 70,000 kt in 2008. This implies that direct emissions from crop and livestock production currently make up approximately 10% of total Canadian emissions in the previous two decades (obtained by dividing the value for agricultural emissions of about 70,000 kt year^{-1} by the total Canadian emissions value of 700,000 kt year^{-1}). Within Ontario, the dairy sector emits approximately 2.64 Mt CO_2eq emissions per year. This is obtained by multiplying the estimated emissions intensity of Ontario milk production from Jayasundara and Wagner-Riddle (2014) by the estimated annual quantity of milk produced in Ontario from DFO (2013).Total estimated emissions from Ontario agriculture are about 10 Mt CO_2eq emissions per year (ECO, 2010), implying that the dairy sector makes up about one quarter of all Ontario agricultural GHGs. The large amount of GHG emissions from milk production in Ontario, and the economic importance of dairy production to the province’s agricultural sector, has led to interest in identifying low cost means of reducing the sector’s GHG emissions.

Figure 1.3 shows that GHG emissions from the Canadian dairy sector have been on the decline in the period 1990-2008. Figure 1.4 shows that emissions intensity (emissions per unit of output) have also been on the decline in this period. Dyer *et al* (2007) finds that the emissions intensity of milk production in Canada has declined due to a nearly 50% drop in the population of the national dairy herd. This has been possible due to an approximate 100% increase in milk yield per milking cow over the previous 3 decades, which has allowed national milk production to remain stable with fewer animals.

The dairy sector emits numerous different gases from a variety of different sources. The three GHGs emitted from the dairy sector are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). After correcting for the global warming potential of these three gases, the emissions sources with the largest impact, in descending order, are methane from enteric fermentation (ruminal digestion of feed), nitrous oxide emissions from agricultural soils, methane and nitrous oxide emissions from manure storage systems, and carbon dioxide emissions from energy use (Jayasundara and Wagner-Riddle, 2014). Further to primary emissions sources as listed above, the dairy sector can indirectly lead to carbon (C) fluxes in or out of soils depending on changes in land use.

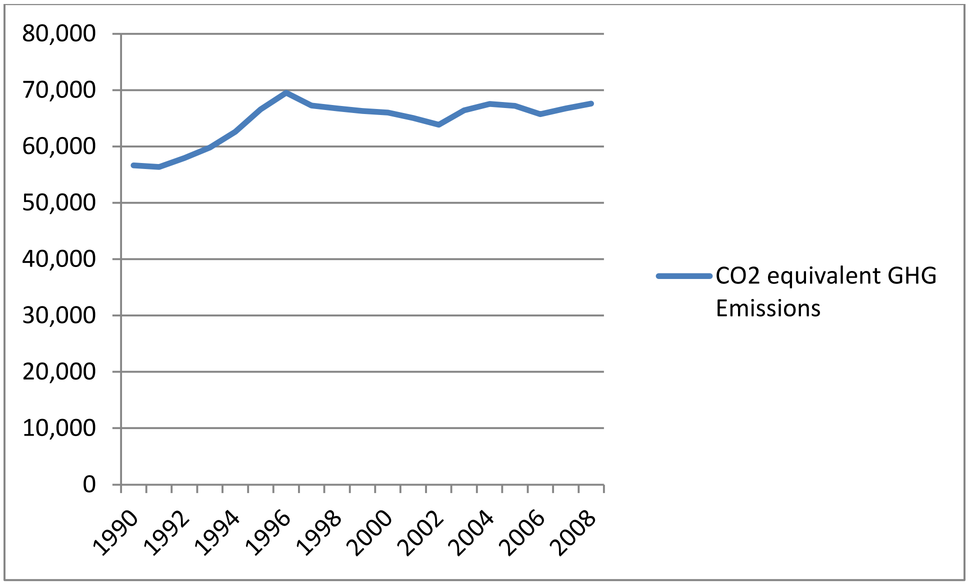
A considerable amount of research has focussed on the role that modifying feed or ration choices has in reducing GHGs from milk production. In particular, Jayasundara and Wagner-Riddle (2014) and Mc Geough *et al* (2012) suggest that future research on GHG mitigation from dairy production in Canada focus on this mitigation strategy. This can be attributed to the large influence of ration choices on each of the emissions sources listed above, suggesting that

Figure 1.1: Upward Trend in Total Canadian GHG Emissions (kt)



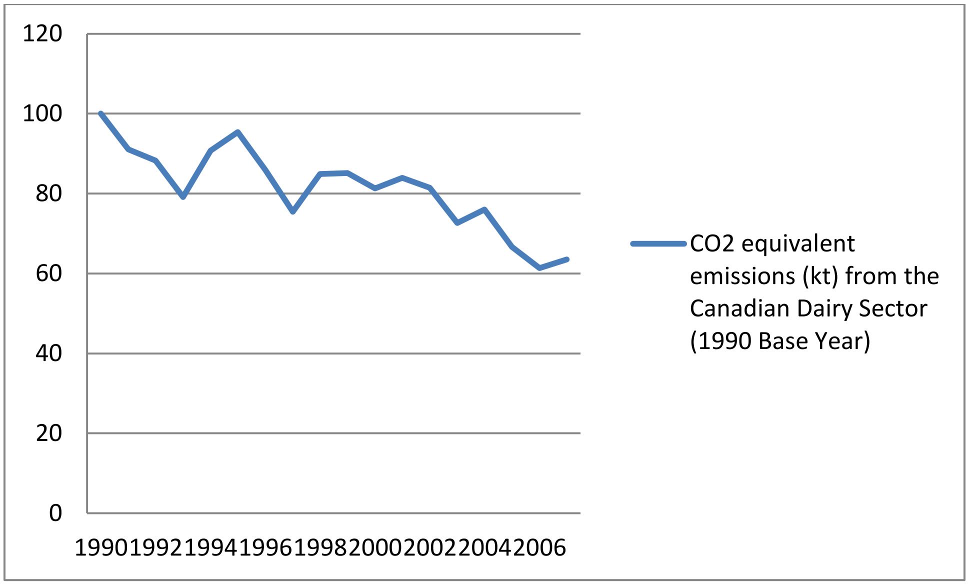
Source: Statistics Canada (2012a)

Figure 1.2: Upward Trend in GHG Emissions (kt) from Canadian Agriculture



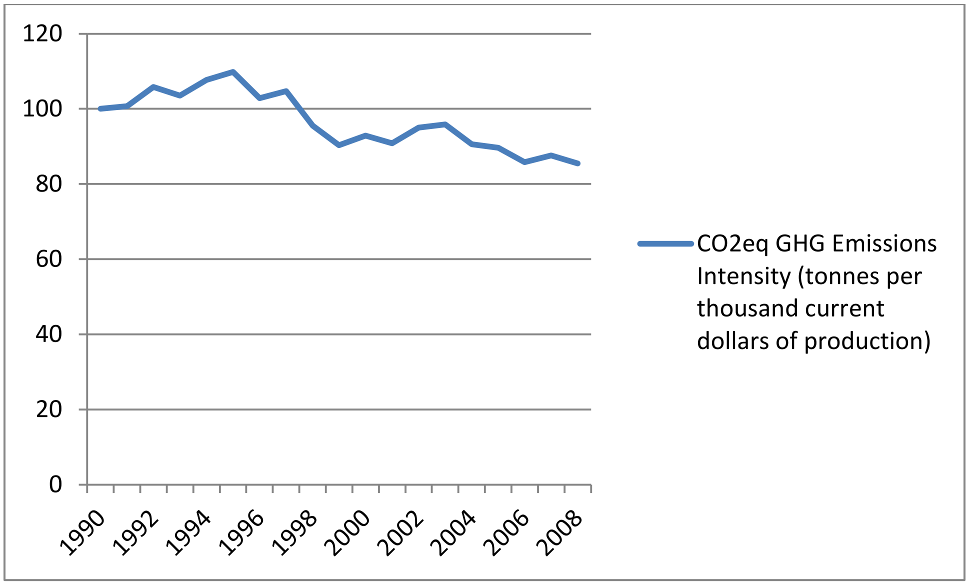
Source: Statistics Canada (2012a)
Note: Agricultural emissions are calculated as the sum of direct emissions from crop and livestock production.

Figure 1.3: Declining Emissions from the Canadian Dairy Sector



Source: Statistics Canada (2012a)
Note: Emissions are both direct and indirect (i.e. upstream and downstream of the farm)

Figure 1.4: Declining Emissions Intensity for the Canadian Dairy Sector



Source: Statistics Canada (2012b)
Note: Intensity is calculated as sum of both direct and indirect CO_2eq emissions divided by value of output of the sector

changes to rations may potentially lead to large declines in GHG emissions from milk production.

The current GHG policy framework in Canada involves regulations on emissions intensity for a variety of industrial and transportation sectors across the country, including power generation, oil and gas, forestry, smelting and refining, iron and steel, mining, cement, lime, and chemicals (Environment Canada, 2007). The regulations involve upper limits on the emissions intensity of the product produced by the industry, where emissions are measured as CO_2eq, and the restrictions are formulated based on estimates of the 2006 emissions intensity of the sector. These measures have been implemented in order to meet the country's goal of reducing GHG emissions to 20% below 2006 levels by the year 2020 (Environment Canada, 2007).

Currently, there exist no regulations directly restricting GHG emissions from the Canadian agricultural sector. While it is unclear what steps will be made by the federal of provincial governments to reduce agricultural GHG emissions in the future, it is unlikely that the same policy framework as in other sectors will be adopted. Numerous studies have identified problems with imposing these types of policies in agriculture, such as Shortle and Horan (2001) and Segerson and Wu (2005). The reason arises from the fact that greenhouse gas emissions from agriculture are characterized as diffuse, with each producer emitting a small fraction of total emissions. Furthermore, there exists significant heterogeneity in emissions, mitigation potential, and mitigation costs, from one producer to the next, depending on the size, location, technology, and management practices on the farm. Policies that rely on precise estimates of farm level emissions are therefore unlikely to be an efficient way of reducing agricultural GHG emissions.

This implies that market mechanisms, such as standards on the emissions intensity of the farm, taxes based on the level of GHG emissions from the farm, or systems requiring producers to purchase permits for GHG emissions, are unlikely, as all of these policies would require substantial costs to the government in order to measure, monitor and enforce emissions from each individual producer (McKitrick, 2010). Instead, policies that enforce specific management practices, or provide incentive for adoption of beneficial management practices (BMPs) on farms have been suggested to be the preferred form of pollution reduction for agriculture (for example, Weersink *et al*, 1998). Examples of these in Canada include Environmental Farming Plans (EFPs), where farmers receive assistance to adopt environmentally friendly practices at low cost. Also, the Nutrient Management Act (NMA) and Clean Water Act (CWA) in Ontario are both regulations that impose binding restrictions to the management of nutrients on crop land.

For purposes of policy development, it is required to identify BMPs that allow GHG emissions in the Ontario dairy sector to be reduced at low cost. The Canadian government has allocated $27 Million in funding to the Agricultural Greenhouse Gas Program (AGGP) in order to identify these practices. From the project's website, the objective of the AGGP program is to "enhance the understanding and accessibility of (1) agricultural technologies, (2) BMPs, or agricultural practices aimed at reducing the environmental impact of farming activities on the landscape, and (3) processes that can be adopted by farmers to mitigate greenhouse gas emissions." (AAFC, 2013b). Future policies aimed at reducing GHG emissions from Canadian agriculture may rely on methods of promoting the widespread adoption of the BMPs identified by this program.

1.1 The Economic Problem

Currently, there are no policies aimed at reducing the Ontario dairy sector's GHG emissions. Given that primary emissions from dairy production, and the production of feed required for dairy cattle, together make up approximately one quarter of all the province's agricultural GHG emissions (ECO, 2010), future efforts to reduce agricultural GHG emissions in Ontario or Canada will likely result in some form of regulation being imposed on the Ontario dairy sector. The economic problem is to reduce GHG emissions associated with milk production in Ontario while having minimal negative economic impact on dairy producers.

The results of this research will inform Ontario dairy producers regarding what options would allow them to reduce GHG emissions at least cost. The Ontario Ministry of Agriculture and Food may also find the research valuable. Knowing the cost effective mitigation strategies at the farm level will form an integral part of any future decision made to reduce the sector's GHG emissions.

1.2 The Economic Research Problem

Numerous authors have employed bio-economic optimization models to estimate GHG mitigation costs, and to identify cost effective mitigation strategies, for various agricultural sectors around the globe. These studies can be classified as farm level or systems level, where the former accounts for activities happening solely at the level of the farm, and the latter accounts for emissions from the farm plus upstream activities associated with production of feed, energy, and other farm inputs. Farm level models are often used for dairy sectors characterized as extensive, with large amounts of feed produced from pasture on the farm, and with purchases of feed making up only a small portion of total feed intake. Studies of this sort include Beukes *et al* (2011 and 2011), Prado *et al* (2009), Adler *et al* (2013), and Doole *et al* (2013). It is required that the model in this study account for the impact of farm management decisions on upstream emissions, as approximately 25% of feed for Ontario dairy farms is obtained off farm (Benke, 2014.). Furthermore, attempts made at reducing emissions on the farm may result in increased levels of emissions upstream from the farm. For example, in a study of the impact of ration choices on enteric methane emissions on California dairy farms, Moraes *et al* (2011) found that the rations that reduced enteric methane resulted in an increase in production of resource intensive crops upstream from the farm, therefore negating the decline in emissions on the farm. There currently exist no studies aimed at determining cost effective GHG mitigation strategies, or estimating GHG mitigation costs, in the Ontario dairy sector. This study therefore seeks to fill this gap in the literature. I account only for the primary emissions sources from milk and crop production (hereafter referred to as cradle-to-farm gate GHG emissions), which includes enteric fermentation, manure, emissions from agricultural soils and from land use change, and emissions from energy use related to farm activities and the production of inputs into farm land. Other emissions sources, such as emissions from manufacturing of machinery and construction of buildings used in production are assumed negligible.

This study focuses solely on one mitigation strategy, feeding or ration choices, and it determines the impact of this decision on net GHG emissions from milk production as well as farm gross margin. I focus on the role ration decisions have in achieving cost effective GHG mitigation because other authors (Jayasundara and Wagner-Riddle, 2014; Mc Geough *et al*, 2012 *)* have identified it as the key mitigation strategy for future emissions reductions in the

Ontario/Canadian dairy sector. The importance of ration decisions arises from its large potential for reducing emissions from the largest sources of emissions within the sector. Changing the concentrate to forage ratio can reduce enteric methane emissions by up to 40% (Benchaar *et al*, 2001). Furthermore, as a significant amount of emissions from dairy production results from production of crops used for feed, changing the rations can result in large reductions in the total amount of emissions from the crop production stage. For example, Adom *et al* (2012) find that GHG intensity (measured as kg CO_2eq emissions per unit of feed) associated with producing grain is about 3.5 times that of producing forage. Furthermore, ration choices have large implications for the profitability of dairy production, as the sum of expenses related to purchased and grown feed on the typical Ontario dairy/crop farm makes up about 70% of total costs (DFO, 2012). This indicates that changing the choice of feeds may result in large changes to expenses and/or revenue for dairy producers.

By developing a model that accounts for the GHG budget for all cradle-to-farm gate GHG emissions, and by holding milk production constant, I am able to identify how rations can change so as to reduce GHG emissions from milk production, and to estimate the corresponding impact on farm profitability. I also account for how changes in land use factor into the GHG budget of milk production. This is a notable feature because one of the few other studies on GHG mitigation in the Ontario dairy sector, Jayasundara and Wagner-Riddle (2014), exclude this emissions category. Switching land from perennial to annual crops, or vice versa, can result in a change in soil carbon storage, as perennial crops are estimated to store about 20% more carbon than annual crops (Guo and Gifford, 2002). Furthermore, other studies have highlighted the importance of land use as an important factor in low cost GHG mitigation from agriculture. In a study assessing farm management decisions on GHG emissions in Canadian agriculture, Desjardins *et al* (2005) find that switching land from crop production to pasture/forage land results in the largest net reduction in GHG emissions out of all the strategies considered. Furthermore, Beauchemin *et al* (2010 and 2011) find that increasing C storage in land is second only to reducing enteric methane emissions in terms of the potential for GHG mitigation in the beef sector in western Canada. It is therefore required to account for how ration decisions can influence the net flux of C into or out of soil, and how this factors into the overall GHG budget of milk production, and to determine whether increasing perennial forages in rations is a cost effective form of mitigation.

1.3 Purpose

The purpose of this study is to identify diet based cost effective strategies to reduce GHG emissions from milk production in Ontario, in order to inform future policy efforts to reduce the sector's emissions. This will inform Ontario dairy farmers regarding how to choose rations so as to reduce GHG emissions. Further, the Ontario Ministry of Agriculture and Food may also benefit from the results, as it is required that the government reduce agricultural GHG emissions in a cost effective manner. Lastly, the research community will benefit from the results of this study. There exists growing interest in identifying low cost means of GHG reduction in crop-livestock systems (for example, FAO, 2006; and FAO 2010). Bio-economic models are one strategy commonly employed towards this end. This study develops a systems level model that can be used to identify cost effective GHG mitigation strategies in the Ontario dairy sector as well as other intensive dairy sectors in Canada and around the world.

1.4 Objectives

1. To develop a bio-economic model of an Ontario dairy/crop farm that purchases off farm feed.
2. To assess the impact of feed choices on GHG emissions from milk production in Ontario.
3. To use the model to determine farm gross margin and the cost-effective choice of feed for a representative Ontario dairy/crop farm when primary GHG emissions from feed and milk production are restricted below their usual levels.

1.5 Chapter Outline

Chapter 2: Overview of the Ontario Dairy Sector

This chapter provides an overview of basic characteristics of the Ontario dairy sector, including data on rations, and the sources of GHG emissions. It discusses the influence of the ration on GHGs from each individual source.

Chapter 3: Empirical Framework

This chapter first defines the farm level economic optimization model, including revenue, costs, farm characteristics, and the procedure used for estimating GHGs.

Chapter 4: Optimization Under Greenhouse Gas Restrictions

This chapter presents and discusses the results of the optimization procedures, including farm financial variables, the rations selected, and GHG emissions.

Chapter 5: Conclusion

This chapter summarizes results and provides some concluding remarks as well as directions for future research and limitations of this study.

Chapter 2

OVERVIEW OF THE ONTARIO DAIRY SECTOR

2.0 Introduction

The purpose of this chapter is to provide a general background of the Ontario dairy sector. First, current formulations of dairy rations are provided. Then estimates of GHG emissions from the sector by each individual source are provided, and the factors determining emissions from each source are described. Since the decision variable of interest for this study is the choice of rations, I describe how this variable impacts each of the individual emissions sources described.

2.1 Rations

Table 2.1 provides estimates of rations for dairy cows and heifers for Ontario in 2011 (Jayasundara and Wagner-Riddle, 2014). The cow rations are made up of 47.4% grains and 52.6% roughages. The heifer rations are made up of 15% grains and 85% roughages. The sources of concentrates in rations are grain corn, soybean meal, and other small grains (barley, wheat, and oats). Grass-legume hays and silages jointly make up the largest fraction of the roughage intake, with corn silage making up the majority of the remaining part of the ration.

2.2 Sources of Greenhouse Gases from the Ontario Dairy Sector

Jayasundara and Wagner-Riddle (2014) estimate GHGs associated with milk production for the Ontario dairy crop complex in 2011 and provide estimates of total emissions, and emissions broken down by source, on an emissions intensity basis (kg CO_2eq kg^{-1} FPCM). Their

Table 2.1: Rations in the Ontario Dairy Sector

Feed	Lactating Cow Rations (% DMI)	Heifers (% DMI)
Grain Corn	15.8	8.3
Soybean Meal	7.9	1.6
Small Grains	17.6	4.4
Supplements	6.1	0.1
Corn Silage	21.8	19.6
Grass-legume Silage	15.1	23.9
Grass-legume Hay	11.5	28.3
Other Roughages	2.4	0.7
Pasture	1.8	13.2
Proportion of Grains	47.4	15.0
Proportion of Roughages	52.6	85.0

Source: Jayasundara and Wagner-Riddle (2014) findings are summarized in Table 2.2. The emission sources arranged from largest to smallest are enteric fermentation, agricultural soils, manure, and energy consumption. While the study did not consider emissions from changes in land use, this category of emissions has an impact as changes in the proportion of perennial to annual crops leads to changes in land use that affects carbon storage in soils. This is of significance as the proportion of perennial forages has been declining in dairy rations since 1990 (Jayasundara and Wagner-Riddle, 2014).

The following sections describe the factors determining emissions from each source. The impact of dairy ration decisions on emissions from each individual source are also explained, so as to provide a thorough description of how this variable impacts GHG emissions in the model developed in Chapter 3.

2.2.1 Enteric Fermentation

Table 2.2 shows that methane emitted from enteric fermentation makes up the largest category of emissions within the sector. Enteric methane emissions depend on the quantity and nutrient properties of feeds fed to animals in the herd. Total feed intake, the proportions of macro nutrients (fat to protein to carbohydrate), the composition of macronutrients (i.e. different types of fat, protein, and carbohydrate), and the level of micronutrients (vitamins and minerals) jointly determine the quantity of CH_4 emitted. Furthermore, the ration also impacts milk yield, which means enteric CH_4 can indirectly be reduced if increased yield allows for greater amounts of milk to be produced relative to the size of the herd.

Table 2.2: Estimates of Sources of GHG Emissions from Ontario Dairy Farms

Emissions Source	Gases	Location	Emissions (kg CO_2eq kg^{-1} FPCM)	% of Total
Enteric Fermentation	CH_4	Farm	0.471	46%
Agricultural Soils – Manure Excreted on Pasture	N_2O	Farm	0.032	3%
Agricultural Soils – Manure Applied as Fertilizer	N_2O	Farm	.07	7%
Agricultural Soils – Synthetic Fertilizer N	N_2O	Farm and Upstream	.048	5%
Agricultural Soils – Crop Residue N	N_2O	Farm and Upstream	.035	3%
Agricultural Soils – NH_3 Volatilization	N_2O	Farm and Upstream	.038	4%
Agricultural Soils – NO_3 Leaching	N_2O	Farm and Upstream	.025	2%
Manure (Storage)	CH_4	Farm	0.133	13%
Manure (Storage)	N_2O	Farm	0.056	5%
Energy – Milking & Related Activities	CO_2eq	Farm	0.023	2%
Energy – Farm Field Work	CO_2eq	Farm	0.035	3%
Energy – Feed Processing/Purchased Feed	CO_2eq	Upstream	0.029	3%
Energy – Production and Transport of Fertilizer and Other Soil Inputs	CO_2eq	Upstream	0.034	3%
Land Use Change	CO_2	Farm and Upstream	-	-
Total	CO_2eq	Farm and Upstream	1.03	100%

Source: Adapted from Jayasundara and Wagner-Riddle (2014)

Non-metabolisable carbohydrates (i.e. cellulose or fibrous plant cell walls) are directly related to rumen methanogenesis (Boadi *et al*, 2004). Replacing fibre with starch and soluble sugars therefore results in diminished methanogenesis. Furthermore, protein and fat are less methanogenic than carbohydrates (Benchaar *et al*, 2001), so replacing fat and protein in place of carbohydrates further contributes to declines in methanogenesis. However, the intakes of protein and fat must be limited so as to preserve the metabolic health of the animal.

In practice, the above principles imply that rumen methanogens are related to the ratio of forage to concentrate in the ration, as well as the quality of forages and concentrates in the ration. Concentrates have more fat, protein, and micronutrients compared to forages. Further, higher quality forages are more nutrient dense relative to lower quality ones. Increasing concentrates at the expense of forages, and replacing low quality forages for higher quality forages is thus seen as a strategy for reducing enteric methanogenesis (Boadi *et al*, 2004).

Benchar *et al* (2001) finds that dietary modification (excluding non-dietary alterations of enteric methane) can result in declines in total enteric methane production by up to 40%. Altering the quantity and quality of forages and concentrates were the most promising mechanisms of reducing enteric methane. Increasing concentrates alone has the potential for a 40% reduction in enteric methane. Replacing fibrous concentrate with starchy concentrate, and use of more digestible forage could result in declines of 22% and 21% respectively. Lastly, reducing ruminally degradable starch and increasing DMI could result in declines of 17 and 7% respectively.

2.2.2 Land allocation and Emissions from Agricultural Soils

Land use impacts both Nitrogen and Carbon cycles in the environment. Table 2.2 shows that N_2O emissions from agricultural soils result from a variety of different processes. While Jayasundara and Wagner-Riddle (2014) do not consider emissions from changes in land use, this category of emissions factors into the calculation of emissions related to milk production.

2.2.2.1 N_2O Emissions from Agricultural Soils

Nitrogen is a major input into the majority of feed crops grown. Nitrogen that is not absorbed by plants may either runoff into surrounding waterways, leach into ground water, or volatilize. Each one of these forms of Nitrogen contributes to N_2O emissions. The level of N_2O emitted per unit of land for different crops varies considerably. Crops that do not require nitrogen inputs, such as soybeans and perennial forages, have minimal N_2O emissions relative to crops that require high N inputs, such as corn or wheat. This implies that this category of emissions varies indirectly depending on choices made regarding the ration. Rations with lesser values of feeds requiring high N inputs will result in less emissions from this category, and vice versa. Table 2.2. shows that N_2O emissions from agricultural soils makes up a total of 24% of total CO_2eq emissions per unit of FPCM, which is the largest source of emissions after enteric fermentation.

2.2.2.2 Carbon Dioxide Emissions from Land Use Change

Changes in land use impacts the flux of carbon in and out of soil. Depending on the change, carbon may either be emitted or sequestered. Guo and Gifford (2002) estimate that there is a 20% increase in carbon storage in perennial crops than there is for annual crops. This implies that choices made for rations may indirectly lead to increases or decreases in soil carbon storage. Switching land from crop production to forages will result in an increase in C storage in land, whereas switching land from forage to crop production will result in a decline in C storage in land. While Table 2.2 does not show how changes in land use have impacted the emissions intensity of milk in Ontario, this category has influenced emissions intensity of milk production in the province. Since 1990, the quantity of land allocated to perennial forages has declined by about 1/3 (Jayasundara and Wagner-Riddle, 2014), indicating that there has been an increase in C emissions due to land use change in this period

2.2.3 Manure

Manure in storage is a source of both CH_4 and N_2O emissions. The amount of emissions depends on a variety of factors, including the length of time the manure is in storage, the quantity and composition of the manure, the manure storage system, and the climatic conditions of the region.

Choices made regarding dairy rations impact the quantity and composition of manure. GHG emissions from manure are positively correlated with the caloric intake of the herd. Also, lower digestible feeds result in greater manure emissions, as there is more undigested feed which ends up being excreted as manure. The ration impacts manure N_2O emissions depending on the amount of protein remaining in manure. This depends jointly on total protein in the diet, and protein retained by the animal. The greater the difference between protein intake and protein requirements, the more N there will be in manure, which contributes to N_2O emissions.

2.2.4 Energy

Table 2.2 shows the activities which consume energy in dairy production, and the corresponding estimates of CO_2eq emissions associated with these activities. In order from largest to smallest, these are farm field work, fertilizer manufacturing, feed processing, and milking.

Ration decisions impact the first three of these categories, but not emissions from milking. The amount of emissions from farm field work varies depending on the type of crop being grown on the land. Certain crops require more or less inputs from machinery. This implies that ration decisions will indirectly influence this emissions category depending on the relative allocation of land between different types of crops.

Similarly, ration decisions also impact emissions from fertilizer manufacturing and feed processing through the same mechanism. Crops vary widely in the amount of fertilizer they receive from conventional farming practices. Also, certain feeds require more processing, and therefore have higher emissions from this category, than do others.

2.3 Summary

This chapter provides basic background information on rations and GHG emissions from the Ontario dairy sector. It identifies the emission sources within the sector and describes the process by which emissions are produced at each one of these sources, as well as how ration decisions influence these emissions. In chapter 3, emissions from these sources will be estimated using conventional estimation procedure, and the impact of changes in rations on the GHG budget of milk production will be determined

Chapter 3

EMPIRICAL MODEL OF A REPRESENTATIVE ONTARIO DAIRY-CROP FARM

3.0 Introduction

The purpose of this chapter is to develop a model to examine the impact of ration decisions on farm gross margin and GHG emissions from milk production. The model is developed to determine how a farm operator could choose rations under a scenario where no restriction on GHGs exists, and one where a GHG emissions intensity restriction is imposed. In both cases, I assume the farm operator's objective is to maximize annual farm gross margin. I assume that GHG emissions are determined by the accounting procedure described below (section 3.4). The decision variable of the model is the rations fed to animals in the herd, or more specifically, the combination of feeds, both from the farm and purchased, that make up the rations. By comparing the rations from the base, unrestricted model, to the restricted ones, it's possible to identify the changes that would have to occur to rations in order to reduce GHG emissions, and what the associated impact on farm profitability is. The parameters of the model are chosen to represent a typical dairy-crop operation in Ontario. Equations are used to estimate emissions from every individual source of GHG emissions (see Chapter 2, section 2) based on the parameters of the model, and the variables which are influenced, directly or indirectly, by ration decisions. In chapter 4, total emissions from milk produced on the farm are restricted in order to determine the impact on farm gross margin, the changes made to the rations, and the resulting changes to each individual source of GHG emissions.

The chapter begins with an overview of the empirical framework that will be used to simulate the representative dairy-crop farm's decisions. The next section discusses the components that determine revenue from the dairy and crop elements of the farm. The following section presents the costs related to milk and crop production, as well as the nutrient restrictions on the rations. The final section defines the procedure used to estimate GHG emissions, and how emissions change with changes in the decision variable.

3.1 Overview of the Conceptual Framework

The basics of the model are illustrated in Figure 3.1. The diagram defines the factors which go into determining the outcomes of interest, namely cradle-to-farm gate GHG emissions and annual gross farm margin. Exogenous factors include factors which are common to all dairy-crop farms in Ontario. These include supply management, the price received for milk, and prices paid for quota. It also includes environmental regulations, namely the nutrient management act (NMA) and clean water act (CWA), which control practices related to nutrient application. I assume the nutrients are managed according to current best management practices in Ontario. Crop and feed prices and weather and geographic conditions are also fairly constant across the province in any given year.

Farm characteristics define the factors which vary among Ontario dairy farms but which influence the outcomes of interest in this study. The number of animals in the herd, as well as the breed and type of animals is relatively constant over time, but may vary highly among dairy farms. The amount of hectares owned by the farm dictates the amount of crops that can be produced, and the soil type dictates the level of fertilizer which must be purchased. Technology, specifically the housing and milking system for dairy cattle, the manure management system, as well as machinery used for managing crop land, are relatively constant over a given production year, but these impact GHG emissions and farm gross margin.

I assume that the farm is based in southwestern Ontario, with a herd size of 150 head of cattle This compares closely to the average Ontario herd size of 146 head per farm, which is calculated by dividing the total number of dairy animals (heifers plus cows) in the province by the total number of dairy farms (from Jayasundara and Wagner-Riddle, 2014). The herd contains three cohorts. Cohorts 1,2 and 3 are comprised of heifers, first parity lactating cows, and second parity lactating cows respectively. Table 3.1 summarizes the herd characteristics. All animals in the herd are Holstein. I assume a replacement rate the same as the actual Ontario value of 37% (CDIC, 2012), and that the ratio of lactating cows to heifers is 2:1. A land area of 150 hectares is devoted to growing crops. These crops can be used directly for feed or sold, thereby providing a source of revenue for the farm. The barn is assumed to be free stall, which is common among larger dairy farms in Ontario (CDIC, 2012). I assume all animals in the herd are housed in the barn year round. Manure is managed as liquid, in an above ground open pit, which is the most common manure management system in Ontario (Sheppard, 2011). For the purposes of GHG estimation (section 3.3) I assume the manure in storage forms a natural liquid crust cover.

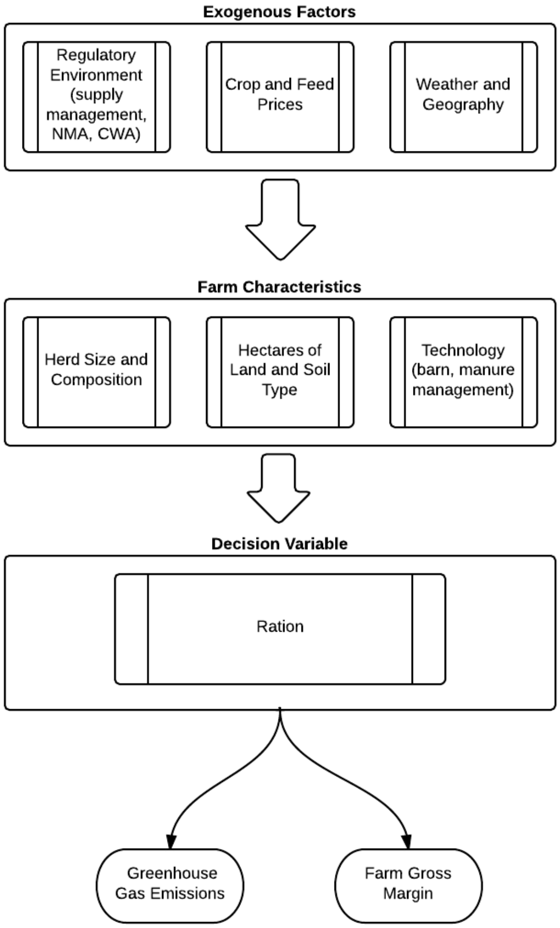
As stated previously, the objective of the operator is assumed to be to maximize annual gross margin. Gross margin is defined as total annual cash revenue minus total annual cash costs. The cash costs do not include expenses related to depreciation of capital or labour costs, and are solely the costs and revenue related to producing and selling milk and crops/feed produced on the farm.

Table 3.1: Herd Characteristics

Cohort (#)	Category	Quantity (head)	Annual Average Weight (kg)	Mature Weight (kg)	Milk Yield (kg hd^{-1} day^{-1})	Milk Yield (hL hd^{-1} $year^{-1}$)	Weight Gain (kg hd^{-1} day^{-1})
1	Heifers	50	480	650	0	0	.5
2	First Parity Cows	50	650	650	26	75.50	0
3	Second Parity Cows	50	650	650	30	87.12	0

Notes: Annual milk yield is based on a 10 month (300 day) lactation period.

Figure 3.1: Schematic Diagram of Conceptual Framework



3.2 Revenue

Revenue is obtained from the sale of milk produced and crops grown on the farm. Revenue is thus defined by the following equation.

$$\text{Revenue} = P_m Q_m + \sum_{c=1}^{3} P_c Q_c^s \qquad [1]$$

Where

P_m the price received for milk in hectolitres
Q_m is the quantity of milk produced and sold in hectolitres
P_c is the price of crop c per mega gram
Q_c^s is the quantity of crop c sold in mega grams

The price received for milk produced is assumed to be the 2012 provincial weighted average price received by dairy farms, which is \$73.51 hL^{-1} (DFO, 2013). This price accounts for the opportunity cost of holding quota and for deductions made for administration, research, DHI, transportation, marketing, and CQM. This price is based on average Ontario milk component traits. I assume that the milk produced by the farm has 3.71% fat and 3.5% protein, which is typical for milk produced in the province (Little *et al*, 2008). I make the simplifying assumption that milk components do not vary as the nutrient content of the rations change, and the nutritional constraints (see below) are specifically chosen to avoid changes in milk yield or milk composition from those assumed by the model.

The base annual milk yield is assumed to be 75.50 hL hd^{-1} $year^{-1}$ for first parity cows and 87.12 hL hd^{-1} $year^{-1}$ for later parity cows. This milk yield is based on the Ontario average milk yield of 28.6 kg hd^{-1} (DHI, 2012), and accounts for an increase in milk yield as cows move from their first to second lactation (Table 3.1). Total annual milk production volume for the farm is therefore $75.50 \times (50) + 87.12 \times (50) =$ 7,981 hL year^{-1}. To convert milk yield from weight in kg to volume in hL, I use a conversion factor of 1.033 kg L^{-1} (IFCN, 2014).

I assume the farm grows corn silage, soybeans, wheat (red winter), and alfalfa hay. The yields and market prices are given in Table 3.2. The prices and yields are the 5 year provincial averages obtained from OMAF (2014b), where yields are based on the years 2009 to 2013, and prices are based on the years 2008 to 2012. Corn silage can be used as feed or sold, with a yield of 41.94 Mg ha^{-1}. I assume corn silage is harvested at 65% moisture content, which is the typical moisture content in the province (OMAF, 2014c), and that there is minimal loss in mass during fermentation, implying that the quantity used as feed is equivalent to the harvested value. Alfalfa hay is assumed to be used exclusively within the dairy operation as feed. The amount of alfalfa and corn silage grown is based on the ration choices along with relative returns from the other cropping choices. Five year averages for yields and prices were used in order to avoid choosing values from a given year that may not represent the long term averages of these values for the province.

3.3 Costs

Costs are divided into two categories: those related directly to dairy production and those related directly to crop production. Together, these costs represent the sum of annual cash costs to the farm. Direct dairy costs are further divided into ration and other direct dairy costs. The ration consists of all feed administered to cattle. Protein and mineral supplements are not included in the model. I assume that the nutrient requirements of the animals can be met solely with feeds.

Table 3.2: Crop Yields and Prices

Crop	Yield (Mg ha^{-1} $year^{-1}$)	Market Price ($ Mg^{-1})
Corn Silage	41.94	50.0
Wheat	5.19	205.7
Soybeans	3.06	435.5
Alfalfa	5.52[a]	-[b]

Sources: OMAF (2014b)

Note: [a] Alfalfa yield includes dry matter and moisture content.

[b] The price for alfalfa is not included because this crop is neither bought nor sold (all alfalfa is grown on the farm specifically to be fed to the herd).

3.3.1 Milk Production

The cost to produce a hectoliter of milk is assumed to be associated with feeding, which is determined endogenously within the model (based on ration choices), plus all other expenses. The non-feed related expense is derived from the Ontario Dairy Farm Accounting Project (DFO, 2012). The average cost per hectolitre of milk produced for all dairy farms in DFO (2012) was \$23.35 with average feed costs, including dairy ration, protein supplements, salt, and minerals, and other purchased feed costs representing \$9.97 hL^{-1}. Thus, non-feed related dairy expense is estimated to be \$13.38 hL^{-1} (=\$23.25-\$9.97).

The ration for cattle is made up of a combination of crops grown on farm and feed purchased off farm. Table 3.3 lists the available feeds, as well as their nutrient properties on a per kg of dry matter (DM) basis, dietary limits (see section on nutrient constraints below), market prices and emission coefficients (see section 3.4 on nitrous oxide emissions from crop land). The constraints on the ration are included to ensure that the animal receives its required energy intake, as well as to ensure that intake of specific nutrients fall within the required range for production and animal health. Milk yields, bodyweights, and growth rates are parameters of the model, and therefore energy supplied by the ration must meet the demands of the animal based on the characteristics assumed. The nutrient constraints are chosen so as to prevent selection of a ration that would lead to a change in any of these characteristics. I have ensured that the energy requirements of the animal are met, and that protein intake cannot deviate widely from typical intakes, in order to ensure that milk yield does not deviate from the assumed value (France, 2014). The feeds are selected to represent the variety of options available to Ontario dairy farms in Ontario, as well as allowing the potential for selection of a ration that can reduce GHG emissions from their typical levels. The nutrient properties of individual feeds are obtained from table 15 of NRC (2001).

The animal energy requirements are expressed on a net energy for lactation (NE_L) basis for lactating cows, and a metabolizable energy (ME) basis for heifers, which is the convention used in NRC (2001). To distinguish between gross energy intake (GEI) from the ration, and the actual energy being received by the animal, equations 2-1, 2-2, and 2-3 of NRC (2001) are used. These equations calculate ME and NE_L at level of intake. They are determined by total digestible nutrients (TDN) in the ration. The ration's TDN value is calculated as the weighted average of each feed's individual value for TDN. The values of TDN for individual feed are obtained from Table 15-1 of NRC (2001).

The NE_L value of the ration for each of the cow cohorts (Mcal kg DM^{-1}) is calculated using the following equation from NRC (2001).

$$NE_L = .0245 \times TDN - .12 \tag{2}$$

Where

NE_L is net energy for lactation (Mcal kg^{-1} DM^{-1})
TDN is total digestible nutrients (%) of the ration

The above value is converted to the daily energy intake (Mcal hd^{-1} day^{-1}) by multiplying by the level of feed intake of the animal (kg hd^{-1} day^{-1}).

Table 3.3: Feed Nutrient Properties, Prices, Dietary Limits, and Emission Coefficients

Feed	Feed Category	NRC Entry #	Price[a] ($ kg^{-1})	TDN (%)	Crude Protein (kg kg^{-1} DM)	ADF (kg kg^{-1} DM)	NDF (kg kg^{-1} DM)	Upper Limit (kg kg^{-1} DMI)	GHG Emissions[b] (kg CO_2eq Mg^{-1})
Alfalfa Hay	Roughage	78	-	.621	.228	.312	.396	1.00	-
Canola Meal	Concentrate	19	.420	.699	.378	.205	.298	0.10	548[c]
Corn DDGS	Concentrate	23	.282	.795	.297	.197	.388	0.20	910
Corn Gluten Meal	Concentrate	25	.594	.844	.65	.082	.111	0.15	390
Corn Grain (Cracked)	Concentrate	26	.250	.85	.094	.034	.095	1.00	390
Corn Silage	Roughage	35	.050	.688	.088	.280	.450	1.00	-
Gluten Feed	Concentrate	24	.218	.741	.238	.121	.355	0.15	390
Grain Oats	Concentrate	90	.322	.785	.132	.146	.3	0.20	850
Grain Wheat	Concentrate	116	.292	.866	.142	.044	.134	0.2	430
Soybean Meal (Expellers)	Concentrate	104	.526	.885	.463	.104	.217	0.15	460
Soybean Meal (Solvent)	Concentrate	107	.526	.814	.538	.062	.098	0.15	460
Vegetable Oil	Concentrate	44	.050	1.841	0	0	0	0.06	460

Sources: All nutrient properties are obtained from Table 15 of NRC (2001). The NRC Entry # refers to the number assigned to each feed from Table 15 of NRC (2001).

[a] Prices for corn grain are obtained from OMAF (2014b). All other prices are obtained from AAFC (2013a)

[b] Adom *et al* (2012)

[c] Government of Manitoba (2014)

Notes: Corn silage and alfalfa hay are the only crops grown on the farm. All other feeds are purchased. GHG emissions associated with growing corn silage and alfalfa hay are not included because they are calculated separately (see section on GHG emissions).

The ME of the heifer ration is calculated by first estimating digestible energy (DE) in Mcal kg^{-1} based on the ration's digestibility using the following equation from NRC (2001).

$$DE = 0.04409 \times TDN \qquad [3]$$

Where

DE is the digestible energy of the ration (Mcal kg^{-1} DM^{-1})

ME is calculated based on DE in the following equation.

$$ME = 1.01 \times DE - .45 \qquad [4]$$

Where

ME is metabolizable energy (Mcal kg^{-1} DM^{-1}) of the ration

The above value is converted to daily energy intake (Mcal hd^{-1} day^{-1}) by multiplying by the level of feed intake of the animal (kg hd^{-1} day^{-1}).

The above equations ensure that energy intake from the ration matches the requirements of the animal. The energy requirements differ from cohort to cohort, as each cohort has animals with different characteristics. For cohort 1 (heifers), energy requirements are for growth and maintenance. For cohorts 2 and 3 (lactating cows), energy requirements are for maintenance and production. Requirements for activity are assumed to be zero because the animals are housed in a free stall barn year round and therefore expend minimal energy on activity.

The following equation calculates energy requirements for maintenance for heifers and cows based on IPCC (2006):

$$NE_M = C_f \times (\text{Average Weight})^{.75} \qquad [5]$$

Where

NE_M is the net energy required for maintenance (Mcal hd^{-1} day^{-1})
C_f is the coefficient of maintenance (MJ day^{-1} kg^{-1})
Average weight is the average weight of the animal (kg hd^{-1})

The coefficient of maintenance takes a value of 0.386 and .322 MJ day^{-1} kg^{-1} for cows and heifers respectively (IPCC, 2006). The following equation calculates energy requirements for gain for heifers based on IPCC (2006):

$$NE_G = 22.02 \times (\text{Average Weight} / (C_d \times \text{Final Weight})) \times ADG^{1.097} \qquad [6]$$

Where

NE_G is the net energy required for gain (Mcal hd^{-1} day^{-1})
C_d is the coefficient of gain and takes a value of 0.8 MJ day^{-1} kg^{-1} (IPCC, 2006)
Final Weight is the final weight of the animal and takes a value of 650 kg hd^{-1}
ADG is the average daily gain and takes a value of .5 kg hd^{-1} day^{-1}

The following equation calculates energy requirements for milk production for cows based on IPCC (2006).

$$NE_P = \text{Milk production} \times (1.47 + 0.40 \times \text{Milk fat content}) \qquad [7]$$

Where

NE_P is net energy for production (Mcal hd^{-1} day^{-1})
Milk production is the quantity of milk produced by the animal (kg hd^{-1} day^{-1}) and is based on the yields given above
Milk fat content is the fat content of milk in percentage and takes a value of 3.71%

Total energy requirements (Mcal hd^{-1} day^{-1}) for cows are the sum of requirements for maintenance and lactation (equations 5 and 7), whereas requirements for heifers are the sum of maintenance and growth (equations 5 and 6). These values are shown in the first row of Table 3.4.In order to determine the nutrient requirements for the animals in the herd, Table 14-7 and 14-14 NRC (2001) are used. Table 14-7 specifies nutrient intakes and sample rations for mature lactating Holstein dairy cows. Column 1 of Table 14-7 shows nutrient intakes and a sample ration for a mature (680kg bodyweight) lactating Holstein dairy cow, producing 25 kg of milk per day. These nutrient intake values are used to set constraints on nutrient intakes for the lactating cows in the model (both cohorts 2 and 3). Crude protein intake for this animal takes a value of 14.1 kg kg^{-1} DMI. The model therefore specifies that the upper and lower bounds on protein are 20 and 10 kg kg^{-1} DMI respectively. The minimum intakes of ADF and NDF for this animal are specified as 25 and 17 kg kg^{-1} DMI respectively. Therefore the model specifies the same minimum values, with maximum values of 35 and 27 kg kg^{-1} DMI respectively (i.e. exactly 10% higher than the minimum value).

From table 14-14, energy requirements in Mcal hd^{-1} day^{-1} for a bred Holstein heifer (450 kg bodyweight) growing at .5 kg day^{-1} is 22.5 Mcal day^{-1}. The characteristics of this animal matches that of the heifers in cohort 1, and therefore the nutrient intakes listed in the table are used to set nutrient restrictions of heifers in the model. The table lists CP intake as .121 kg kg^{-1} DMI. The model therefore specifies upper and lower bounds of .2 and .05 kg kg^{-1} DMI respectively. The table does not give specific constraints on fibre, so the equivalent constraints for cohorts 2 and 3 are assumed.

Additional constraints on all cohorts of cattle include lower bounds for calcium and phosphorous, limits on total forage intake and NDF from forage, and an upper limit on added dietary lipid. These constrains were chosen in discussion with (Wright, 2014) and (France, 2014). The constraints are summarized in table 3.4.

The below equation defines the costs to the farm to purchase feed, which is the sum of each individual feed purchased multiplied by its respective price.

$$\text{Feed Costs} = \sum_{j=1}^{10} P_j^{fd} Q_j^{fd} \qquad [8]$$

Where

P_j^{fd} is the market price of feed j per kg

Q_j^{fd} is the amount of feed j in kg purchased and fed to cattle

3.3.2. Crop Production

Annual expenses for growing a crop are based on OMAF's Publication 60 (OMAF, 2014a). These costs are summarized in Table 3.5. These costs include all expenses related to maintaining crop land, excluding those related to the purchase and application of nutrients (both organic and inorganic fertilizer). These costs are calculated separately based on the quantity of each type of fertilizer applied. The costs in Table 3.5 include those related to seeding, tractor and machine expenses, herbicides and insecticides, marketing fees, trucking, crop insurance, drying, operating labour, and storage. The cost for alfalfa is adjusted to account for both establishment (seeding) costs as well as the annual maintenance cost. Since the type of tillage does not affect

Table 3.4: Summary of Animal Nutrient Constraints

Dietary Property	**Required Value or Range**		
	Heifers	**First Parity**	**Second Parity**
Required Energy Intake[a] (Mcal hd^{-1} day^{-1})	22.5	37.7	41.2
Crude Protein Intake(kg hd^{-1} day^{-1})	$0.05 \leq$ Crude Protein Intake $\leq 0.2\times$ DMI		
Acid Detergent Fibre (kg hd^{-1} day^{-1})	$.17\times$ DMI $\leq$ ADF $\leq .27\times$DMI		
Neutral Detergent Fibre (kg hd^{-1} day^{-1})	$.25\times$ DMI $\leq$ NDF $\leq .35\times$ DMI		
Phosphorous (kg hd^{-1} day^{-1})	Phosphorous $\geq 0.003\times$ DMI		
Calcium (kg hd^{-1} day^{-1})	Calcium $\geq 0.003\times$ DMI		
Total Roughage Intake (kg hd^{-1} day^{-1})	$0.5\times$ DMI $\leq$ Roughage Intake $\leq 0.6\times$ DMI (Cows) $0.5\times$ DMI $\leq$ Roughage Intake $\leq 0.8\times$ DMI (Heifers)		
Forage NDF (kg hd^{-1} day^{-1})	$0.2\times$ DMI $\leq$ NDF from Forage		
Total Lipid Intake (kg hd^{-1} day^{-1})	Total Lipid Intake $\leq 0.03\times$ DMI		

Notes:[a] Energy intake is calculated as net energy for lactation for cows and metabolizable energy for heifers.

GHG emissions in Ontario, differing types of tillage can be assumed for each crop type and these will not factor into estimates of GHG emissions. I assume that soybeans and wheat are not tilled. Costs associated with crop production on the farm are the sum of the per hectare costs plus the costs of purchasing and applying fertilizers. The management costs for crops 1 to 4 (corn, soybean, wheat, and alfalfa respectively), excluding costs of fertilizer are summarized as follows.

$$\text{Crop Costs} = \sum_{c=1}^{4} C_c A_c \qquad [9]$$

Where

C_c refers to the per hectare cost of managing crop c
A_c refers to the total hectares devoted to crop c

The crop rotation is included in the model by allocating a fixed fraction of total workable land to each crop. I assume the total time required for one crop rotation is 6 years. At any given point in time, the minimum value of total land that can be allocated to each crop is 10% for corn, soybeans, and wheat, and 15% for alfalfa. The following equations describe the limits for each crop’s proportion of total land.

$$A_1 \leq \frac{T_{corn}}{\bar{T}} \times A_T \qquad [10]$$

$$A_2 \leq \frac{T_{soy}}{\bar{T}} \times A_T \qquad [11]$$

$$A_3 \leq \frac{T_{wheat}}{\bar{T}} \times A_T \qquad [12]$$

$$A_4 \leq \frac{T_{alfalfa}}{\bar{T}} \times A_T \qquad [13]$$

Where

T_{corn} is the number of years corn crops are grown on a hectare of land for one crop rotation cycle
T_{wheat} is the number of years wheat crops are grown on a hectare of land for one crop rotation cycle
T_{soy} is the number of years soy crops are grown on a hectare of land for one crop rotation cycle
$T_{alfalfa}$ is the number of years alfalfa crops are grown on a hectare of land for one crop rotation cycle
A_1, A_2, A_3,A_4 is the minimum amount of land allocated to corn, wheat, soybeans, and alfalfa at a given point in time
$\bar{T}$ is the total number of years of one crop rotation cycle

Nutrient requirements for each crop can be provided from inorganic (purchased synthetic fertilizer) or organic (manure from dairy cows) sources. I assume that the ratio of nutrients provided by organic and inorganic fertilizer can change without any impact on either crop yield or GHG emissions from farm soils. Typical Ontario application rates of N, P, and K are assumed, based on Publication 60 (OMAF, 2014a). These requirements are summarized in Table 3.5. The costs for N,P, and K fertilizers are listed in Table 3.6, along with the application cost, based on OFIMP (2012) and Wilson (2014) respectively.

The following equation denotes the total cost of purchasing and applying N, P, and K fertilizer on crop land. N, P, and K fertilizers are denoted as i = 1, 2, and 3 respectively.

$$\text{Inorganic Fertilizer Costs} = \sum_{i=1}^{3} C_i^f Q_i^f \qquad [14]$$

Where
C^f_i is the total cost of purchasing and applying a kg of fertilizer i
Q^f_i is the total amount of inorganic fertilizer i purchased and distributed on cropland

Table 3.5: Crop Costs and Nutrient Requirements

Crop	**Cost ($ ha^{-1} year^{-1})**	**N Requirement (kg ha^{-1} yr^{-1})**	**P Requirement (kg ha^{-1} yr^{-1})**	**K Requirement (kg ha^{-1} yr^{-1})**
Corn Silage	$605.00	140	20	50
Wheat	$489.80	100	20	40
Soybeans	$496.22	0	20	40
Alfalfa	$473.75	0	40	30

Sources: OMAF (2014a)

Table 3.6 Fertilizer Costs

	Price[a] ($/kg)	**Application Cost[b] ($/kg)**	**Total Fertilizer Costs ($/kg)**
Nitrogen	$1.65	$0.09	$1.74
Phosphorous	$2.54	$0.09	$2.63
Potassium	$1.57	$0.09	$1.66

Source: [a] OFIMP (2012) [b] Wilson (2014)

I make the simplifying assumption that the nutrient composition of manure remains constant as the composition of the ration changes. While changes in feed composition may have an impact on the nutrient content of manure, I assume the effect on financial or environmental properties of the model is small enough to be negligible. I assume that all nutrients are managed according to current best management practices in Ontario, implying that nutrients are not applied in excess of the crop's requirements. NMAN3 software (OMAF, 2013) is used to estimate nutrient content of manure for the herd based on standard nutrient values of manure from dairy cattle fed typical rations. The values are 0.43% (4.3 kg Mg^{-1}), .1% (1 kg Mg^{-1}) and .27% (2.7 kg Mg^{-1}) for N, P and K respectively. In order to obtain an estimate of the quantity of manure produced, equations from Nennich *et al* (2005) are used. These equations estimate manure produced per animal in kg based on DMI (kg hd^{-1} day^{-1}) and body weight (kg hd^{-1}). The equations used for predicting total manure production are summarized in Table 3.7. To determine the cost of applying manure, I assume a mass to volume conversion factor of 0.266 gal kg^{-1}, which is the typical mass to volume conversion rate for dairy manure(University of Vermont, 2014) . The cost of applying manure is assumed to be \$.02 gal^{-1} based on OMAFRA's 2012 custom farm work survey (OMAFRA, 2013). The cost of applying manure is summarized by the following equation.

$$\text{Manure Application Costs} = M_c \times M_P \qquad [15]$$

Where

M_c is the cost to apply a gallon of manure
M_p is the total gallons of manure produced and applied on the farm

The total cost for the farm is calculated as the sum of crop, synthetic fertilizer and manure application costs, which is the sum of equations 9, 14, and 15. . Annual farm gross margin is calculated as the difference between annual revenue and annual costs. This implies annual farm gross margin is equal to equation 1 (revenue) minus equations 9, 14, and 15 (costs).

3.4 Greenhouse Gas Emissions

The following section describes the procedure used to estimate the level of GHG emissions associated with producing milk on the farm. The sources accounted for are (1) CH_4 emissions from enteric fermentation, (2) CH_4 and N_2O emissions from manure storage, (3) N_2O emissions from land used to grow crops on the farm, (4) CO_2 sequestered/emitted from changes in land use, (5) CO_2eq emissions related to direct energy consumption and with manufacture of upstream products used for feed production, and (6) CO_2eq emissions associated with purchased feed production. To obtain an estimate of net CO_2eq emissions associated with milk production, emissions from all sources are converted to CO_2eq by multiplying CH_4 emissions and N_2O emissions by the global warming potentials of 25 and 298 respectively (IPCC, 2006), and then adding them together.

3.4.1 Enteric Fermentation

The ration affects enteric fermentation and thus the level of CH_4 generated by the animal. The following equation from Ellis *et al* (2007) defines daily CH_4 (MJ) emissions per head as a function of the animal's DMI (kg hd^{-1} day^{-1}), and intakes of ADF (kg hd^{-1} day^{-1}), and NDF (kg hd^{-1} day^{-1}).

Table 3.7: Manure Production Equations

Animal Category	Equation
Heifers (cohort 1)	Manure Produced (kg hd^{-1} day^{-1}) = DMI (kg hd^{-1} day^{-1}) × 4.158 – BodyWeight (kg hd^{-1}) × 0.0246
Cows (cohorts 1 and 2)	Manure Produced (kg hd^{-1} day^{-1}) = DMI (kg hd^{-1} day^{-1}) × 2.63 + 9.4

Source: Nennich *et al* (2005)

Note: Bodyweight for heifers takes a value of 480 kg hd^{-1}

$$CH_4^{EF} = 2.16 + 0.493 \times DMI - 1.36 \times ADF + 1.97 \times NDF \qquad [16]$$

Where

CH_4^{EF} is methane emissions from enteric fermentation (MJ CH_4 hd^{-1} day^{-1})
DMI is the animal's dry matter intake (kg hd^{-1} day^{-1})
ADF is the animal's intake of acid detergent fibre (kg hd^{-1} day^{-1})
NDF is the animal's intake of neutral detergent fibre (kg hd^{-1} day^{-1})

I used this equation because it was found to have a high degree of accuracy in estimating enteric methane production for dairy animals by Escobar *et al* (2013). The estimated CH_4 emissions are converted from MJ to kg of CH_4 using a conversion factor of 55.58 MJ kg^{-1} CH_4^{-1} (EPA, 2014). Emissions from animals in all three cohorts are summed up and converted to annual farm CH_4 emissions from enteric fermentation.

3.4.2. Manure

The ration affects the quantity and composition of manure and consequently methane and nitrous oxide emissions. To estimate annual CH_4 emissions from manure in the above ground, open pit storage, equations from IPCC (2006) are used. The first step calculates volatile solids (VS) in kg hd^{-1} day^{-1} in the manure using the following equation.

$$VS = GEI \times ((1\text{-}TDN) \times 100^{-1}) + .04 \times GEI \times ((1\text{-}Ash) \times 100^{-1}) \times 18.45^{-1}. \qquad [17]$$

Where

VS is volatile solids (kg hd^{-1} day^{-1})
Ash is the ash content of the ration (%)
GEI is gross energy intake (MJ hd^{-1} day^{-1})

TDN and ash all depend on the properties of the ration. Gross energy intake (GEI) is in MJ and is calculated based on the digestibility of the ration in the following three equations from IPCC (2006). The first equation is as follows.

$$REM = 1.123 - (0.004092 \times TDN) + (0.00001126 \times TDN^{2}) - (25.4 \times TDN^{-1}) \quad [18]$$

Where

REM is the ratio of net energy available in the diet for maintenance to digestible energy consumed

The second equation is as follows.

$$REG = 1.164 - (0.005160 \times TDN) + (0.00001308 \times TDN^{2}) - (37.4 \times TDN^{-1}) \quad [19]$$

Where

REG is the ratio of net energy available in the diet for gain to digestible energy consumed

Next, gross energy intake of the animal is calculated according to the following equation.

$$GEI = (((NE_M + NE_P) \times REM^{-1}) + (NE_G \times REG^{-1})) \times (100 \times TDN^{-1}) \quad [20]$$

Where

GEI is gross energy intake (MJ hd^{-1} day^{-1})
NE_M is net energy for maintenance (from equation 5)
NE_P is net energy for production (from equation 7)
NE_G is net energy for gain (from equation 6)

TDN (%) is calculated as described in section 3.3.1 above. Ash content of the ration is in percentage terms (%) and is calculated as the sum of ash content of each individual feed divided by DMI. Ash content of each individual feed is obtained from NRC (2001). To estimate CH_4 emissions (kg hd^{-1} day^{-1}), the following equation is used

$$CH_4^M = VS \times Bo \times MCF \times .67 \qquad [21]$$

Where

CH_4^M is the methane produced from manure (kg hd^{-1} day^{-1})
B_0 is the methane producing capacity (m^3 CH_4 kg^{-1} VS)
MCF is the methane conversion factor

B_O takes the IPCC (2006) default value of 0.24 m^3 CH_4 kg VS^{-1}. I assume a value for MCF of 0.18. This assumes that the average MCF for Ontario liquid manure systems without a natural crust cover is 0.3 (Little *et al* 2008) corrected for a 40% reduction in MCF by having a crust cover (IPCC 2006). The above value is converted to annual herd CH_4 emissions. IPCC (2006) equations are also used to estimate annual N_2O emissions from stored manure. First, dietary protein intake from the ration is estimated through the following.

$$PI = (GEI \times CP \times DMI^{-1}) \times 18.45^{-1} \qquad [22]$$

Where

PI is the protein intake of the animal (kg hd^{-1} day^{-1})
CP is the crude protein intake of the animal (kg kg^{-1} DMI)

The N content of manure is obtained by subtracting protein retained for gain (PRG) and protein retained for lactation (PRL) according to the following equation.

$$\text{Nitrogen Excretion} = PI \times 6.25^{-1} - PRL \times 6.38^{-1} - PRG \times 6.25^{-1} \qquad [23]$$

Where

Nitrogen Excretion is the nitrogen excreted in the animal’s manure (kg hd^{-1} day^{-1})

PRL is estimated from the following equation from IPCC (2006).

$$\text{PRL} = \text{Milk Yield} \times \text{Milk Protein} \qquad [24]$$

Where

PRL is protein retained for lactation (kg hd^{-1} day^{-1})
Milk yield is the milk produced by the cow (kg hd^{-1} day^{-1})
Milk Protein is the protein content of milk (kg kg^{-1})

Milk yield is based on productivity assumptions given by cow parity as discussed above and milk protein is assumed to be 0.035 kg kg^{-1}, as described above. PRG is calculated according to the following equation from NRC (2000).

$$\text{PRG} = \text{ADG} \times (268\text{-}(29.4 \times (\text{RE} \times \text{ADG}^{-1}) \times 1000^{-1} \qquad [25]$$

Where

PRG is protein retained for gain (kg hd^{-1} day^{-1})
ADG is the average daily gain of the animal (kg hd^{-1} day^{-1})
RE is the retained energy (Mcal hd^{-1} day^{-1})

RE is estimated as

$$\text{RE} = 0.0635 \times \text{EBW}^{0.75} \times \text{EBG}^{1.097} \qquad [26]$$

Where

EBW is empty body weight (kg $hd^{-1)}$
EBG is empty body gain (kg hd^{-1} day^{-1})

Empty body weight is equal to Average Weight $\times 0.891$, and empty body gain is calculated as Average Daily Gain $\times 0.956$. The direct and indirect N_2O emissions from stored manure can then be calculated as follows.

$$N_2O^M = \text{Nitrogen Excretion} \times (EF_{Direct} + FRAC_{Vol} \times EF_{Vol}) \qquad [27]$$

Where

N_2O^M is manure nitrous oxide emissions (kg hd^{-1} day^{-1})
EF_{Direct} is the direct emission factor with a value of 0.005 (IPCC, 2006)
EF_{Vol} is the volatilized emission factor with value of 0.01 (IPCC, 2006)
$FRAC_{Vol}$ is the fraction of N present in manure that is volatilized and takes a value of 0.40 (IPCC, 2006).

N_2O^M is then converted to annual herd N_2O emissions from stored manure.

3.4.4 Crop Nitrous Oxide

The ration affects emissions from crop production as it changes the relative proportion of land allocated to different types of crops. To estimate total annual N_2O emissions from the farm land used to grow crops for feed, a per hectare emission rate is obtained for each type of crop using Holos GHG estimation software (Little *et al*, 2008). Given the characteristics of the farm described in 3.1, the N_2O emissions (kg ha^{-1}) are 4.08 kg N_2O $year^{-1}$ ha^{-1} for corn, 2.126 kg N_2O $year^{-1}$ ha^{-1} for wheat, 0.343 kg N_2O $year^{-1}$ ha^{-1} for soybeans, and 0.31 kg N_2O $year^{-1}$ ha^{-1} for alfalfa. Total annual crop N_2O emissions (kg) from the 150 hectares of farmland are therefore dependant on the amount of land allocated to each crop.

3.4.5 Carbon from Land Use Change

Converting land from annual to perennial crops (or vice versa) leads to carbon being sequestered (or emitted from the farm). As the only perennial crop grown on the farm is alfalfa, a change in land allocated to this crop can alter GHG emissions. The following equation from McConkey *et al* (2007) calculates carbon (g m^{-2} yr^{-1}) sequestered/emitted from a change in land use.

$$\Delta C = 3691 \times (\exp^{-.0241(y-1)} - \exp^{-.0241y}) \qquad [28]$$

Where

ΔC is the carbon emitted/stored (g m^{-2} yr^{-1}) from land use change on the farm
3691 is the maximum C emitted/stored by a management change in a geographic region characterized as mixed wood plains (typical in southwestern Ontario) (g m^{-2})
y is the amount of time since the management change
0.0241 is the rate constant for switching from annual to perennial crops

To assess the immediate effect of a change in land use, it is assumed one year has passed since the management change (and therefore $y = 1$). The total carbon sequestered/emitted from a change in the farm's land use is summed together, multiplied by 10 and 44/12 to convert from g m^{-2} to kg ha^{-1} and from C to CO_2. The resulting value of 3,248.1 kg CO_2eq ha^{-1} is the per hectare annual quantity of CO_2eq emissions (kg) associated with an increase or decrease in land allocated to alfalfa on the farm. If the amount of land allocated to alfalfa increases (decreases), this takes a negative (positive) value.

3.4.6 Carbon Dioxide from Energy Consumption

To estimate CO_2 emissions from spreading manure on the field, it is assumed that energy required to spread 1000 litres of manure is .0248 GJ (Little e*t* al, 2008). A conversion factor of 70 kg CO_2 GJ^{-1} is used to convert energy consumption to the corresponding CO_2 emissions using diesel powered machinery (National Inventory Report, 2010). The result is an estimate of 1.736 kg of CO_2 emissions per 1000 litres of manure spread. Similarly, an annual value of 19,360 kg of CO_2 emissions related to milking was obtained by converting annual electricity required per milking cow of 968 kWh (Verge *et al*, 2007) by a conversion factor of 0.2 kg CO_2 kWh^{-1} (National Inventory Report, 2010).

The total amount of synthetic N and P fertilizer purchased by the farm are multiplied by 3.59 kg CO_2 kg N^{-1} and 0.569 kg CO_2 kg P_2O_5 to convert kg of fertilizer used to the corresponding CO_2 emissions required for manufacturing (Nagy, 2000). The energy requirements to produce herbicide in GJ ha^{-1}, based on the amount applied on each crop, are 0.12 for corn, 0.24 for wheat, 0.12 for soybeans, and 0 for alfalfa (Dyer and Desjardins, 2007). After the total amount of energy required for producing herbicide for the farm is obtained, a conversion factor of 5.8 kg CO_2 GJ^{-1} is used to calculate CO_2 emissions associated with production.

To estimate CO_2 emissions from farm field work, estimates of the total amount of machine energy consumption required to manage specific types of crops are obtained from Dyer and Desjardins (2007). These values in GJ ha^{-1} of 3.29 for corn, 1.34 for wheat, 1.72 for soybeans, and 0.81 for alfalfa are multiplied by a conversion factor of 70 kg CO_2 GJ^{-1} to calculate total CO_2 emissions associated with meeting these energy requirements from diesel powered farm machinery used to do the field work associated with growing the crops.

3.4.7 Emissions From Feed Production Upstream from the Farm

To estimate emissions from the production of feed upstream from the farm, estimates of cradle-to-farm gate emissions associated with feed production are obtained from Adom *et al* (2012) and Government of Manitoba (2014). These emission coefficients (kg CO_2 Mg^{-1} of feed), which are summarized in the last column of table 1, are multiplied by the amount of feed used in the ration to calculate the total upstream emissions from feed production.

3.5 Summary

This chapter defines the objective function and decision variable of the model and identifies the model's properties. Revenue is the sum of income from the sale of milk and crops produced on the farm. Costs are broken into those related to the dairy operation and those related to the crop operation. The decision variable is the choice of feeds that make up the rations for the three cohorts of animals in the herd. To account for GHG emissions, emissions from each source are added together to obtain an estimate of total annual cradle-to-farm gate CO_2eq emissions. The next chapter presents the results of the model with and without a restriction on GHGs.

Chapter 4

OPTIMIZATION UNDER GREENHOUSE GAS RESTRICTIONS

This chapter presents and discusses the results of the restricted and unrestricted scenarios of the model, including financial variables, ration decisions (both ration composition and ration nutrient properties), and GHG emissions. The results from the unrestricted scenario are compared to available data to verify that the model provides realistic results. In section 4.2, the impact of the GHG restriction on the model output is described. The chapter concludes with a general discussion of the findings and the implications of the results.

4.1 Base Model

The model is run initially without any restrictions on GHG emissions. Total GHGs associated with producing milk are estimated at 786,940 kg CO_2eq year^{-1} (see Table 4.1). The emissions intensity associated with milk production is therefore 0.945 kg CO_2eq kg^{-1} FPCM, which is obtained by dividing the annual GHG emissions from producing milk in the model by the annual quantity of FPCM produced by the farm (recall assumptions regarding milk composition in chapter 3). This value is consistent with the estimated provincial average of 1.03 kg CO_2eq kg^{-1} FPCM, and falls within the estimated provincial range of .89 to1.36 kg CO_2eq kg^{-1} FPCM (Jayasundara and Wagner-Riddle, 2014). The maximum annual return to the producer is \$539,930 year^{-1}. This value is consistent with actual returns from large dairy-crop enterprises in Ontario of \$414,000 year^{-1} (DFO, 2012).

The farm purchases a total of 305 Mg year^{-1} in feed, consisting of corn grain, gluten feed, and vegetable oil. The allocation of land is such that the majority of the 150 hectares owned by the farm is allocated to growing corn silage (both for feed and sale), with lesser amounts allocated to wheat, and soybeans. No land is allocated to alfalfa. Land is allocated on the farm such that corn silage takes up the maximum allowable area allowed by the model (65% of total land area), while wheat, soybeans, and alfalfa take the lowest allowable values (10, 10, and 0% respectively). The rations chosen in the base model are consistent with Ontario ration formulations estimated by Jayasundara and Wagner-Riddle (2014), in which heifers have rations consisting of 14.3% grains and soybean meal, 19.6% corn silage, and 66.1% grass-legume and other roughages, and cows have rations consisting of 41.3% total grains and soybean meal, 21.8% corn silage, and 30.8% grass-legume and other roughages, and 6.1% supplements. Cow rations in the model have concentrate to roughage ratios of 40:60 and these compare to actual values of 47:53 (Jayasundara and Wagner-Riddle, 2014). Heifer rations in the model have concentrate to roughage ratios of 30:70, which compares to actual values of 15:85 for heifers.

Table 4.2 provides a breakdown of the nutrient properties of the rations. The higher digestibility (TDN) or relative to actual Ontario rations results in a lower GEI and lower DMI for all three rations compared to actual Ontario rations. Recall that the energy supplied by the ration must match the requirements of the animal, and therefore a highly digestible ration requires less total energy (GEI) and a lower DMI compared to a less digestible ration, as a higher proportion of the total caloric intake is being received by the animal for productive purposes (i.e. maintenance, growth, and milk production). The lower DMI for the heifer ration is also partly explained by the lower body weight assumed for heifers in the model (480 kg hd^{-1}) compared to average bred heifer body weights of about 550 kg hd^{-1} (NRC, 2001) accounted for in Jayasundara and Wagner-Riddle (2014). I chose 480 kg hd^{-1} as the bodyweight of the heifer cohort in order to

Table 4.1 Gross Margin and Variable Choices for Base Model and GHG Restricted Models

		GHG Restrictions				
Variable	**Base**	**5% Restricted**	**10% Restricted**	**20% Restricted**	**30% Restricted**	**35% Restricted**
Net Returns (% Decline)	\$539,930	\$536,030 (0.7)	\$515,550 (5.5)	\$473,660 (12.2)	\$431,320 (20.0)	\$409,270 (24.20%)
GHG Emissions	786,940 kg CO_2eq year^{-1}	747,590 kg CO_2eq year^{-1}	708,250 kg CO_2eq year^{-1}	629,552 kg CO_2eq year^{-1}	550,858 kg CO_2eq year^{-1}	511,900 kg CO_2eq year^{-1}
Land Use						
Corn - Silage	75%	75%	69%	50%	33%	23%
Wheat	15	10%	10%	10%	10%	10%
Soybeans	10%	10%	10%	10%	10%	10%
Alfalfa	-	5%	11%	39%	47%	57%
Feed Purchased (Mg year^{-1})						
Corn Grain	177	252	256	273	290	295
Gluten Feed	104	23	18	9	-	-
Vegetable Oil	24	24	24	25	25	26
Ration Choice						
Heifers						
Corn - Grain	23.4	23.0	21.9	21.7	21.6	21.6
Corn - Silage	70.0	60.9	30.0	23.1	21.1	21.1
Alfalfa	-	10.1	44.5	52.2	54.3	54.3
Gluten	3.6	3.0	0.6	-	-	-
Vegetable Oil	3.0	3.0	3.0	3.0	3.0	3.0
1st Parity Cows						
Corn - Grain	22.0	34.0	34.3	35.8	37.0	37.0
Corn Silage	60.0	60.0	55.7	35.8	15.7	5.4
Alfalfa	-	-	4.3	24.2	44.3	54.6
Gluten	15.0	3.0	2.7	1.2	-	-
Vegetable Oil	3.0	3.0	3.0	3.0	3.0	3.0
2nd Parity Cows						
Corn - Grain	22.0	34.0	34.3	35.8	37.0	37.0
Corn - Silage	60.0	60.0	55.7	35.8	15.7	5.4
Alfalfa	-	-	4.3	24.2	44.3	54.6
Gluten	15.0	3.0	2.7	1.2	-	-
Vegetable Oil	3.0	3.0	3.0	3.0	3.0	3.0

Source: Model Output

capture the range of weights for young (less than one year) and mature (greater than one year) heifers.

Table 4.2 provides a breakdown of the nutrient properties of the rations. The higher digestibility (TDN) or relative to actual Ontario rations results in a lower GEI and lower DMI for all three rations compared to actual Ontario rations. Recall that the energy supplied by the ration must match the requirements of the animal, and therefore a highly digestible ration requires less total energy (GEI) and a lower DMI compared to a less digestible ration, as a higher proportion of the total caloric intake is being received by the animal for productive purposes (i.e. maintenance, growth, and milk production). The lower DMI for the heifer ration is also partly explained by the lower body weight assumed for heifers in the model (480 kg hd^{-1}) compared to average bred heifer body weights of about 550 kg hd^{-1} (NRC, 2001) accounted for in Jayasundara and Wagner-Riddle (2014). I chose 480 kg hd^{-1} as the bodyweight of the heifer cohort in order to capture the range of weights for young (less than one year) and mature (greater than one year) heifers.

Table 4.3 provides a breakdown of GHG emissions. It accounts for all emissions sources based on the procedure described in section 3.4, and also shows estimated net cradle-to-farm gate emissions, which is the sum of emissions from each individual source. Since land allocated to alfalfa increases, the land use change category takes on a negative value (see section 3.4.5),

Table 4.2: Ration Nutrient Properties

Animal Category or Scenario	Dry Matter Intake (kg hd^{-1} day^{-1})	Total Digestible Nutrients (%)	Gross Energy Intake (kg hd^{-1} day^{-1})	Crude Protein Intake (%)	Acid Detergent Fibre Intake (%)	Neutral Detergent Fibre Intake (%)
Estimated Nutrient Properties for Ontario in 2011[a]						
Heifers	9.5	65.1	175.3	14.8	31.9	49.8
Cows	20.5	73.9	378.2	17.2	21.1	36.5
Model Output						
Heifers						
Base	7.64	76.20	134.55	9.2	20.8	35.0
5% Restricted	7.79	74.93	137.83	10.5	21.7	35.0
10% Restricted	8.37	70.46	150.64	15.0	23.4	35.0
20% Restricted	8.51	69.48	153.83	16.0	25.6	35.0
30% Restricted	8.55	69.19	154.79	16.3	25.7	35.0
35% Restricted	8.55	69.19	154.79	16.3	25.7	35.0
1st Parity Cows						
Base	17.20	76.62	303.48	10.9	19.4	34.4
5% Restricted**	16.89	77.93	297.02	9.2	18.3	31.3
10% Restricted	17.00	77.44	299.40	9.8	18.6	31.1
20% Restricted	17.55	75.18	310.94	12.3	19.9	30.4
30% Restricted	18.14	72.89	323.75	15.0	21.2	29.7
35% Restricted	18.47	71.66	331.12	16.4	22.0	29.5
2nd Parity Cows						
Base	18.80	76.62	331.82	10.9	19.4	34.4
5% Restricted	18.47	77.93	324.77	9.2	18.3	31.3
10% Restricted	18.59	77.44	327.36	9.8	18.6	31.1
20% Restricted	19.19	75.18	339.99	12.3	19.9	30.4
30% Restricted	19.83	72.89	353.98	15.0	21.2	29.7
35% Restricted	20.20	71.66	362.05	16.4	22.0	29.5

Sources: [a] Jayasundara and Wagner-Riddle (2014). Everything else is from the model output.

indicating GHGs are being sequestered rather than emitted from this change. The base model's emissions intensity from each individual source is provided in order to compare to the estimates of the emissions intensity of milk production in Ontario provided by Jayasundara and Wagner-Riddle (2014). These values are shown (kg CO_2eq kg^{-1} FPCM) in the first column of the table. The estimates of emissions intensity in Ontario correspond very closely with the results of the base model.

The model calculates on farm and off farm GHG emissions from feed production separately, which prevents a direct validation with Jayasundara and Wagner-Riddle (2014), as this paper does not distinguish between on farm and off farm crop production. However, total emissions related to feed production in the model are 0.279kg CO_2eq kg^{-1} FPCM (sum of farm soil emissions, upstream emissions associated with feed production, and energy emission from farm field work and manufacture of inputs). From Jayasundara and Wagner-Riddle (2014), total emissions related to feed production (based on the same categories of emissions) are .347 kg CO_2eq kg^{-1} FPCM, indicating that this component of emissions is quite close to estimates of actual values in Ontario.

The consistency of farm gross margin, ration formulations, and GHG emissions determined by the base model with empirical data on the Ontario dairy sector suggests that the model accurately represents actual dairy farming conditions in the province. The differences in rations can be attributed to the low relative cost of concentrates in the model, which leads to a higher intake of these crops relative to roughages. This affects the nutrient properties of the rations by having a higher TDN value, and a slightly lower DMI and GEI. The estimation of GHG emissions by the base model predicts values that are highly consistent with the findings of Jayasundara and Wagner-Riddle (2014).

4.2 Restricted Model

Results for GHG restrictions at 95, 90, 80, 70, and 65% (the maximum restriction level) of the original GHG levels are provided in tables 4.1, 4.2, and 4.3. Values for these levels of restriction are provided to allow for a thorough analysis of how the GHG restriction impacts the model output at varying stringencies of the GHG restriction. Emissions cannot be reduced below 65% of their original levels, implying a maximum reduction of 35% from the base level of emissions. The maximum level of restriction results in a decline in farm returns of 24.2% from the original value. Feed purchases change such that purchases of gluten feed approach zero, while corn grain increases. Purchases of vegetable oil remain constant at 3% in all simulations, which is the upper bound for this feed. Land allocated to alfalfa on the farm steadily increases, going from 0 to 57% of farm land. Land allocated to corn silage steadily declines, going from 75% to 23% of farm land. Land allocated to producing soybeans remains constant, with that of wheat declining from 15 to 10% (note these feeds are not part of the rations).

The changes to the composition of the rations is that alfalfa replaces corn silage to become the sole source of roughage (except for the heifer ration), and corn grain replaces gluten feed to become the sole source of concentrate in the rations. The least emitting ration for the cows consists of alfalfa hay at 54.6% of DMI, corn silage at 5.4% of DMI, corn grain at 37% DMI, and vegetable oil at 3% of DMI. The heifer ration consists of alfalfa hay at 54.3% of DMI, corn

Table 4.3: Greenhouse Gas Emissions for Base Model and GHG Restricted Models

			Restricted Simulations				
GHG Source (Gas)	**Actual Values** (kg CO$_2$eq kg^{-1} FPCM)	**Base Emissions** (kg CO$_2$eq) (kg CO$_2$eq kg^{-1} FPCM) 833043	**5%** (kg CO$_2$eq) (change (kg CO$_2$eq)) (% change)	**10%** (kg CO$_2$eq) (change (kg CO$_2$eq)) (% change)	**20%** (kg CO$_2$eq) (change (kg CO$_2$eq)) (% change)	**30%** (kg CO$_2$eq) (change (kg CO$_2$eq)) (% change)	**35%** (kg CO$_2$eq) (change (kg CO$_2$eq)) (% change)
Enteric Fermentation (CH$_4$)	.471	377,790 (.454)	359,610 (-18,180) (-4.8%)	360,550 (-17,240) (-5.0%)	359,150 (-18,640) (-5.0%)	357,690 (-20,100) (-5.3%)	357,910 (-19,880) (-5.3%)
Manure (CH$_4$)	.134	139,140 (.167)	133,140 (-6,000) (-4.3%)	142,900 (+3,760) (+2.7%)	158,500 (+19,360) (+13.9%)	174,320 (+35,180) (+25.3%)	183,100 (+43,960) (31.6%)
Manure (N$_2$O)	.053	19,275 (.023)	14,982 (-4,293) (-22.2%)	20,102 (+827) (+4.3%)	29,090 (+9,815) (+50.9%)	38,307 (+19,032) (+98.7%)	43,474 (+24,199) (+125.6%)
Farm Soils (N$_2$O)	.247	14,257 (.018)	13,975 (-282) (-2.0%)	13,417 (-840) (-5.6%)	12,061 (-2,196) (-15.4%)	10,662 (-3,595) (-25.2%)	9,935 (-4,322) (-30.3%)
Land Use Change (CO$_2$)	- -	- -	-8,360 (-8,360) -	-56,076 (-56,076) -	-142,080 (-142,080) -	-228,690 (-228,690) -	-273,850 (-273,850) -
Energy – Total (CO$_2$eq)	.121	116,020 (.139)	115,860 (-160) (-0.1%)	118,250 (2,230) (2%)	91,469 (-24,551) (-21.2%)	73,705 (-42,315) (-36.5%)	64,444 (-51,576) (-44.5%)
Energy – Farm Field Work	.035	30,025 (.036)	29,859 (-166) (-.6%)	27,827 (-2,198) (-7.3%)	23,192 (-6,833) (-22.8%)	18,523 (-11,502) (-38.3%)	16,089 (-13,936) (-46.4%)

(CO_2eq)							
Energy – Fertilizer and Herbicide Manufacturing (CO_2eq)	.034	63,554 (.076)	63,586 (32) -	58,789 (-4,765) (-7.5%)	45,707 (-17,847) (-28.1%)	32,533 (-31,021) (-48.8%)	25,664 (-37,890) (-59.6%)
Energy – Milking (CO_2eq)	.023	19,360 (.023)	19,360 (0) -	19,360 (0) -	19,360 (0) -	19,360 (0) -	19,360 (-) -
Energy – Manure Spreading (CO_2eq)	-	3,081 (.004)	3,056 (-25) (-0.8%)	3,126 (+45) (+1.5%)	3,209 (+128) (+4.2%)	3,288 (+117) (+3.8%)	3,331 (250) (+8.1%)
Purchased Feed[a] *(CO_2eq)*	-	120,460 (.145)	118,380 (-2,080) (+1.7%)	118,250 (-1,280) (-.8%)	121,360 (+900) (+.7%)	124,870 (+4,410) (+3.6%)	126,890 (+6,440) (+5.3%)
Net Total Cradle-to-farm Gate (CO_2eq)	1.03	786,940 (.945)	747,590 (-39350) (-5.0%)	708,250 (-78,690) (-10.0%)	629,550 (-157,390) (-20.0%)	550,860 (-236,080) (-30.0%)	511,900 (-275,040) (-35.0%)

Source: [1] Jayasundara and Wagner-Riddle (2014). All other results are from the model output

Notes: [a] Farm soils refers only to soils on the modelled farm and does not include emissions from crop production upstream from the farm

[b] Purchased feed includes emissions from primary production as well as processing

silage at 21.1% of DMI, corn grain at 21.3% DMI, and vegetable oil at 3% of DMI. The concentrate to roughage fractions of the cow rations remain constant at 40 to 60, with that of the heifers increasing from 30:70 to 25:75.

The nutrient properties of all three rations undergo the same changes (Table 4.2). The digestibility (TDN) of the rations decline, due to the higher intake of alfalfa hay, which has a lower TDN value compared to corn silage (58.8%, as opposed to 68.9% for corn silage (NRC, 2001)). The GEI and DMI of all three rations increases, as the lower intake of digestible nutrients requires that a higher total caloric intake and DMI is need to meet the energy requirements of the animal. There is an increase in CP, which can also be attributed to the higher intake of alfalfa hay, which has a higher CP content than corn silage (22.8% for alfalfa hay vs. 8.8% for corn silage). There is a decline in NDF and an increase in ADF in the cow rations. ADF for the heifers increases, while NDF remains constant.

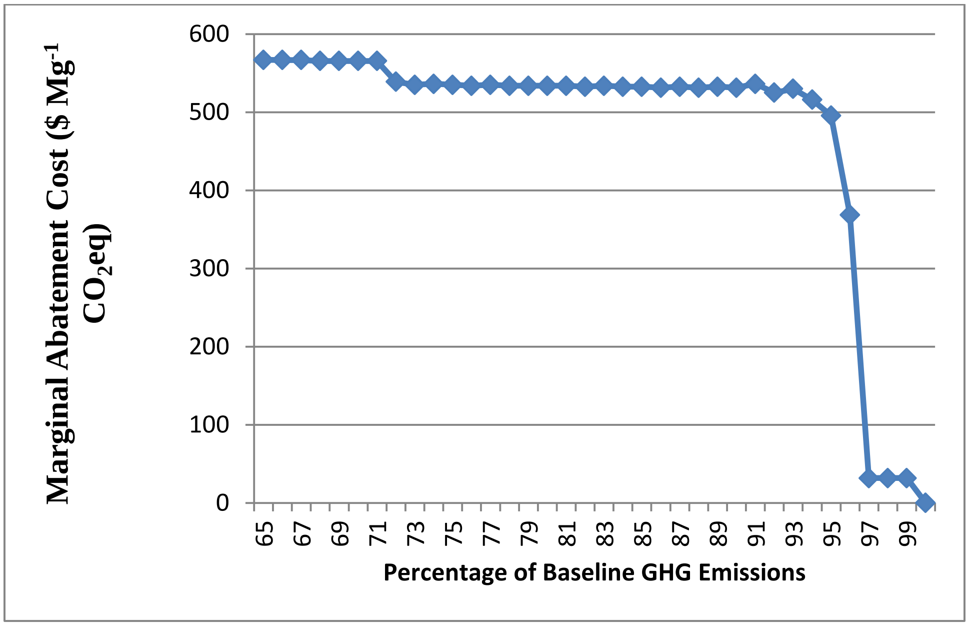
The changes in the rations affect every source of GHG emissions accounted for in the model, with the effect varying in magnitude and in direction (i.e. some sources increase, others decrease). This implies that the interactions between the choice of ration and the various emissions sources lead to trade-offs that must take place in order for GHGs to be restricted to the maximum level at least cost. The large increase in production of alfalfa and the corresponding land use change on the farm leads to a large increase in CO_2 sequestration (i.e. a negative emissions source). In the maximally restricted scenario, this category makes up about 100% of the net decline in emissions of 275,040 kg CO_2eq year^{-1} from the base model's emissions, implying that the other sources experience a net zero change in GHG emissions. Emissions from energy consumption decline by 51,576 kg CO_2eq year^{-1}, which is attributable to the lower inputs required for growing alfalfa compared to corn silage on the farm (see section 2.3.5) Recall that energy consumption accounts for emissions from farm field work, manure spreading, chemical inputs, and milking. Due to the fact that milking related emissions remain constant in the model (since the choice of ration does not affect electricity consumed during milking), the change in emissions from the energy category is attributable solely to the three remaining emissions sources, which are all related to machine and chemical inputs on farmland. The change in energy emissions can therefore be attributed solely to changes resulting from the change in land allocation. Switching from corn silage to alfalfa as the primary feed crop grown on the farm therefore leads to less GHG emissions from energy use and production of inputs used on the farm, which along with declines in N_2O from soils, and C sequestered from land use change, leads to a large reduction in emissions associated with producing the rations fed to the herd.

Methane from enteric fermentation declines, which is attributable to the decline in NDF in the cow rations (see equation 7 from chapter 3). Both manure methane and nitrous oxide increase. This is caused by the rise in GEI and decline in TDN of the rations, which has a positive effect on manure methane (see equations 8-12 from chapter 3), and the rise in CP and GEI, which has a positive effect on manure nitrous oxide (see equations 13-18 from chapter 3).

In order to assess the impact of the GHG restriction on gross farm margin, Figure 4.1 shows the marginal abatement cost curve. The MAC curve represents the marginal cost of emissions reductions for various levels of GHG emissions. The marginal abatement cost is less than \$50 Mg^{-1} CO_2eq for GHG levels above 96% of baseline, but thereafter there is a sharp increase in the marginal cost of abatement. After GHG emissions have reached 95% of baseline, the marginal abatement cost is \$500 Mg^{-1} CO_2eq. From Table 4.3, it can be shown that the source of GHG mitigation is primarily from declines in methane from enteric fermentation and methane and nitrous oxide from manure in the first 4% of mitigation. Together, these two categories make up about 72% of the net decline in emissions for this stage. This stage of mitigation is primarily resulting from the replacement of gluten feed with corn silage in the rations, as the total intake of alfalfa and corn silage by the herd remain relatively constant. The resulting change in nutrient properties of the rations is what causes the decline in emissions from enteric fermentation and manure. The decline in gross farm margin for this stage is low.

For emissions declines after 4% of baseline, the further decreases in emissions from enteric fermentation are relatively small (about 0.5% from the original value), while manure emissions begin to increase. For this range of mitigation, the amount of land allocated to alfalfa begins to increase, and the cost to the farm to supply feed in the form of alfalfa is greater than that of corn silage (crop production costs are \$86 Mg^{-1} for alfalfa vs. \$14 Mg^{-1} for corn silage). This implies that for mitigation in the range 5-35%, the primary source of emissions reductions is resulting due to the replacement of corn silage with alfalfa in the rations, which results in a larger marginal abatement cost than in the first segment (0-5%) of emissions reductions.

Figure 4.1: Marginal Abatement Cost Curve



Source: Model Output

4.4 Discussion

The results of this study indicate that the choice of feeds for dairy herds have major implications for GHG emissions from dairy production in Ontario. The maximum level of GHG restriction is 35% below the base level of GHG emissions. Each individual source of GHG emissions accounted for is affected differently, with the effect varying in magnitude and direction (i.e. some increase, others decrease).

Furthermore, the results indicate that GHG emissions can be reduced a small amount at low cost to the farm, but that mitigation greater than about 5% results in a much larger impact on farm gross margin. The first stage of mitigation results from declines in herd emissions (enteric fermentation and manure). The second stage results from the change in land allocation on the farm, which leads to a net flux of C into farm soils, and lower GHG emissions from agricultural soils and from consumption of inputs into crop production.

The primary difference between cow ration formulations of the maximally restricted scenario and current Ontario cow ration formulations is that the NDF content of the model's ration is significantly lower than that estimated by Jayasundara and Wagner-Riddle (2014). Based on equation [16] from chapter 3, the lower NDF content of the maximally restricted rations may lead to lower enteric methane emissions than current Ontario rations. From NRC (2001), alfalfa hay has a lower NDF content than other common forage feeds, namely corn silage and alfalfa silage. Having a high intake of this feed therefore reduces the total NDF content of the rations.. This suggests that obtaining the roughage component of the ration from alfalfa hay as opposed to other roughages may result in lower methane produced from enteric fermentation compared to current Ontario dairy rations.

In the maximally restricted scenario, approximately 100% of the net GHG reduction is occurring directly due to the sequestration of carbon resulting from land use change on the farm. Compared to the base model, emissions from enteric fermentation in the maximally restricted scenario are about 5.3% lower. Emissions from manure are higher, due to the higher GEI and lower digestibility of the ration (see section 3.4.2). This results in an increase in total emissions from enteric fermentation and manure (i.e. the herd). This implies that, in order to obtain the maximum level of GHG mitigation, the rations change such that emissions associated with the crop production stage (i.e. agricultural soils, land use, and inputs into farmland) are lower, while those from the herd are higher.

The finding that replacing corn silage with alfalfa leads to a decline in emissions from crop production, with a negligible impact on herd emissions, can be attributed to the similarity in nutrient properties of the two feeds, but wide variation in emissions from producing them. The digestibility of corn silage and alfalfa hay are 68.8% and 62.1% respectively (NRC, 2001). The values for ADF and NDF are 28% and 45% for corn silage and 31% and 40% for alfalfa (NRC, 2001). Since GHGs from enteric fermentation and manure depend on these properties (see section 3.4 on emissions from manure and enteric fermentation), the relative fraction of each in the ration has little implication for direct emissions from the herd. However, the large difference in emissions from producing the two feeds means that the relative proportion of the two in rations will have major implications for emissions from producing the ration. This is due to a combination of the lower inputs required to grow alfalfa relative to corn silage, the lower N_2O emissions from land used to grow alfalfa relative to corn silage, and lastly C sequestration by land allocated to alfalfa (see section 3.4 on GHGs). From Holos GHG estimation software (Little *et al*, 2008), emissions from growing corn silage in Ontario, with yield and nutrient application corresponding with those assumed by my model, are 1,442.5 kg CO_2eq ha^{-1} $year^{-1}$ (this includes N_2O emissions from agricultural soils as well as energy related emissions from machinery and inputs into land). The estimated emissions for a hectare of land recently (one year having passed) allocated to alfalfa is -2,343.6 kg CO_2eq ha^{-1} $year^{-1}$. The C sequestered by land allocated to alfalfa exceeds the sum of soil N_2O and energy related emissions from inputs into land, making the hectare of land a net sequesterer, as opposed to source, of GHG emissions. This indicates that, when the C storage capacity of perennial forages are accounted for in the model, the relative fraction of perennial to annual roughages in the ration (and the corresponding land use) has critical implications for the GHG budget of milk production.

Other studies on GHG mitigation in livestock-cropping systems consistently find that selecting rations that minimize methane produced from enteric fermentation is a critical component of the overall effort to achieve cost effective abatement. As mentioned previously, enteric methane is the single largest source of GHG emissions from dairy production, making up nearly half of the emissions intensity of 1.03 kg CO_2eq kg^{-1} FPCM in Ontario (Jayasundara and Wagner-Riddle, 2014). Furthermore, the large influence of feed on this emissions source implies that choosing rations to minimize enteric methane is a crucial component of cost-effective mitigation. For example, both Lovett *et al* (2006) and Beukes *et al* (2011) find that cost effective GHG mitigation involves feeding high levels of concentrates in the Irish and New Zealand dairy sectors respectively, in order to keep enteric methane production low. Beukes *et al* (2011) find that an emissions intensity of .8 kg CO_2eq kg^{-1} FPCM can be attained on New Zealand pastoral dairy farms through a combination of mitigation strategies, involving lower DMI and high intake of concentrates. Lovett *et al* (2006) find that in order to minimize GHG emissions per unit of milk production in the Irish dairy sector, it is required to feed a concentrate intake near the upper allowable limit (about 50% of DMI). This latter study is similar to mine in that the higher emissions associated with producing concentrates upstream from the farm were considered, indicating that the trade-off between enteric methane and emissions from producing energy intensive crops must take place in order to achieve cost effective GHG mitigation.

The results of my study indicate that it is possible to select a ration that both minimizes the sum of emissions from crop production, while keeping enteric methane low. This is consistent with other studies on GHG mitigation in ruminant farming systems in Canada. Beauchemin *et al* (2011) find that beef farms in western Canada become net sinks of GHG emissions when existing cropland is reseeded with grass, indicating that feed choices can result in GHG mitigation due to the change in emissions from agricultural soils. Furthermore, Beauchemin *et al* (2010) find that, after minimizing enteric methane production, increasing soil C stocks is the largest potential source of GHG mitigation in the beef sector in western Canada. Together these studies suggest that rations must be chosen to keep enteric methane at a minimum (i.e. by having a high concentrate to roughage component) but by selecting feeds to keep emissions associated with producing the feeds going into the rations low.

The findings herein may provide relevant insight into how to reduce GHG emissions from the Ontario dairy sector. Currently, cow rations in Ontario have about 23% DMI as corn silage, and about 27% DMI as perennial forages (Jayasundara and Wagner-Riddle, 2014). The results of this study suggest that obtaining as large a fraction of the roughage component of rations from high quality perennial forages, will lead to modest reductions in enteric methane, and a large reduction in GHG emissions from feed production.

The MAC curve indicates the cost of reducing GHG emissions from dairy production in the Ontario dairy sector. As is discussed above, the marginal abatement cost sharply increases once alfalfa begins to replace corn silage in the rations, as a result of the difference in costs to the farmer to supply roughage from alfalfa as opposed to corn silage. For the first stage of mitigation (from 0 to 5%), the cost of reducing emissions is below $50 Mg^{-1} CO_2eq. For the remainder of the GHG mitigation, the cost of reducing emissions ranges between $500 to $600 Mg^{-1} CO_2eq. These findings are relevant to the development of policies in Ontario and Canada to achieve cost effective GHG mitigation.

The prices for crops/feeds used in my model are based on calculated average Ontario prices for the years 2007-2012. In 2013 and 2014 the price of corn declined by approximately 40%, from the 2012 value of $260 Mg^{-1} to the current price of $ 163 Mg^{-1}(AAFC, 2014). This change in price does not imply that the mitigation costs Ive estimated are unrealistic, because corn makes up a large fraction of the rations regardless of whether the GHG restriction is imposed or not. The base rations have high levels of corn silage and gluten feed (a derivative of corn), whereas the restricted rations have little corn silage or gluten but high values of corn grain. This suggests that farm gross margin would have taken larger values for all simulations of the model had I used recent prices as opposed to 2007-2012 average prices. This would not be the case had I assumed the farm obtains all corn on-farm, as it would not be subject to volatility in feed prices and instead its costs would be based solely on the costs of producing corn, which remain relatively constant from one year to the next.

From Moraes *et al* (2011), the cost of reducing enteric methane emissions from U.S. dairy farms ranges from \$604 to \$9,935 Mg^{-1} CO_2eq emissions. Since I find that at the maximum level of restriction, the cost of emissions reductions is about \$550 Mg^{-1} CO_2eq emissions, my findings suggest that GHG mitigation costs in confinement dairy systems in Canada are less expensive than in the U.S.. Further, I account for the entire GHG budget of milk production, which indicates that when these emissions sources are taken into account GHG mitigation costs may be less than those estimated by Moraes *et al* (2011). However, even the mitigation costs I find for the Ontario dairy sector are lower than GHG mitigation costs in other sectors of the economy.

Market prices in Carbon markets around the world ranged from about \$7 to \$142 Mg^{-1} CO_2eq emissions in 2012 (The Climate Group, 2012). Out of all jurisdictions where carbon taxes are in place around the world, tax rates varied from \$4 to \$615 Mg^{-1} CO_2eq in 2012 (The Climate Group, 2012). When comparing these ranges of GHG mitigation costs to the results of my study, obtaining GHG mitigation below the 5% in the Ontario dairy sector would require carbon prices at the high end of the range of prices currently in place around the world. This implies that the

Canadian and/or Ontario governments may be able to reduce their respective jurisdictions GHG emissions at lower cost by imposing GHG mitigation policies on sectors other than the dairy sector. This finding, however, is based on the design of the model in this study.

Chapter 5

Conclusion

5.1 Summary

The objective of this thesis was to determine the rations that allow GHGs to be reduced in the Ontario dairy sector at least cost. I constructed a bio-economic model to assess how changing rations on a typical Ontario dairy-crop farm affects all cradle-to-farm gate emissions sources. The model is notable in that it accounts for every major source of GHG emissions related to milk production, both on the farm and upstream. These include emissions from enteric fermentation, manure, agricultural soils, and energy. The model therefore accounts for the total impact of ration modification on net cradle-to-farm gate GHG emissions, and estimates the impact of this on farm gross margin. The results indicate that changing the ration can lead to declines in GHG emissions from milk production of up to 35% from original levels. At the maximum level of restriction, there is a total decline of 24.2% in farm gross margin.

5.2 Findings

Both the data on current rations in the Ontario dairy sector, and the results of the base optimization procedure, indicate there is little room for reducing emissions from enteric fermentation or manure through ration modifications. There is however large potential for GHG reductions by replacing corn silage with low C footprint and low resource input perennial forages, such as alfalfa or Timothy hays or silages. Due to the similarity in nutritional properties between perennial forages and corn silage, this change has minimal impact on emissions from enteric fermentation and manure, but results in a decline in net emissions from crop production, largely due to the difference in C storage potential of perennial versus annual crops.

5.3 Implications

Current dairy cow rations in Ontario have about 23% of DMI from corn silage. Furthermore, the trend in the previous decades has been towards less perennial forages, and more corn silage in rations. Cow rations in 1990 had 42.3% DMI as perennial forages. This value declined to 30.8% by 2011 (Jayasundara and Wagner-Riddle, 2014). This has been part of the overall decline in roughages in rations, which have declined from 68.3 to 52.6% DMI for cows in the same period. Perennial forages have therefore become a lesser part of the total roughage content of rations in previous decades. This may be due to financial reasons, as average prices of alfalfa hay have been more than 4 times that of corn silage over the previous 5 years. From OMAF (2014b), the 5 year (2008-2012) average Ontario price for corn silage is \$34 Mg^{-1}, with a corresponding value of \$144 Mg^{-1} for alfalfa hay. Furthermore, as noted above, the costs of producing corn silage are significantly lower than alfalfa, as well as other hays/grasses. By obtaining the roughage fraction of dairy rations from high quality perennial forages, emissions associated with milk production will decline, primarily due to the flux of C into farm soils, which has a major impact on the GHG budget of milk production. The results herein, however, suggest this may lead to a significant increase in costs for dairy producers.

5.4 Limitations and Suggestions for Future Research

For this thesis, I have developed a model to assess the role that decisions made regarding the formulation of rations can play in cost effective GHG mitigation in the Ontario dairy sector. This model has relied extensively on equations published in the scientific literature related to the estimation of GHG emissions from the variety of sources within the dairy sector. I've attempted to account for GHG emissions so that I use an accurate estimation procedure, but there is inevitably a margin of error associated with the system Ive used. Constructing bio-economic models necessarily depends on having accurate systems of GHG accounting, and therefore future research refining procedures to estimate GHG emissions from crop and livestock systems, and the impact of mitigation strategies on these emissions, will be helpful for this.

In order to complete the objectives of this thesis in the simplest manner, I have excluded components that would add complexity to the model without significantly improving the results. I have not accounted for changes in nutrient content of manure. Given that the protein intake of all three rations increases as the GHG restriction is imposed, it is foreseeable that these changes to the rations would result in increased excretion of N in manure (as protein intake is primary factor affecting N excretion in manure). I do, however, ensure that nutrient application matches the requirements for the crop, and therefore I can assume that there will not be excessive nutrient leaching.

I used parameters in my model so as to represent a typical commercial dairy/crop farm in southwestern Ontario. I only modelled one farm, and therefore it remains unclear how heterogeneity among dairy-crop farms (i.e. size, technology, location) influence mitigation costs. Furthermore, geographic location is known to play a large influence in C sequestration in soils, indicating that the amount of mitigation obtained from land use change may vary highly depending on the location of the farm within Ontario. There are certain emissions sources not accounted for in the model, including transportation of feed, and emissions from production of K fertilizer. The model does not allow for mineral or protein supplements fed to cattle, and this may have resulted in ration formulations that would differ were these to be included.

Given that I have addressed the topic of how rations can be chosen so as to reduce GHG emissions at least cost, future research may want to address other mitigation strategies to determine whether these strategies are more or less cost-effective than modifying the ration. For example, manure management is a crucial aspect of GHG mitigation in the dairy sector as emissions from this source make up a large fraction of total emissions. Future studies may seek to develop models to determine cost effective mitigation when an assortment of different mitigation strategies are considered.

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Appendix - GAMS Code

```
SETS
        h herd composition /1*3/
        heifers(h) /1/
        firstparity(h) /2/
        secondparity(h) /3/
        lact(h) /2*3/

        n nutrient properties  /TDN, CP, DE, ADF, NDF, Ca, P, Limit /
        c merged index for all uses of land and feed purchased off farm /1*20/
* Subindices
        land(c) subindex for all land uses(crop and non-crop) /1*6/
        crp(land) subindex for all crops grown on farm /1*4/
        ann(crp) subindex for all annual crops /1*3/
        ncland(land) subindex for all non-crop land uses /5*6/
        fd(c)      subindex for crops and off farm feed or supplement being fed to cattle
/1*4,7*20/
        alf(crp)    subindex for alfalfa crop          /4/
        allmkt(crp) /1*3/
        mkt(crp) subindex for crops going to market only /2,3/
        fdmk(crp)   subindex for crops going to market and for feed /1*3/
        offs(fd)     subindex for off farm feeds   /7*20/
        forage(fd) index for all forages /4,1,12,13,14/
        rough(fd) /1,4,12,13,14/
        conc(fd) /7,8,9,10,11,15,16,17,18,20/
        seq(land) index for all land uses that sequester carbon /4*6/
        fat(fd) index for fats fed to cattle /19/
$ontext
List of feeds/crops making up 'c' index (note elements 5 and 6 are empty)
        1 = corn silage
        2 = soybeans
        3 = wheat
        4 = alfalfa hay
        5 = -
        6 = -
        7 = corn ddgs
        8 = oats
        9 = corn silage
        10 = soybean meal
        11 = soybean meal
        12 = alfalfa silage
        13 = grass 1
        14 = grass 2
        15 = corn grain
        16 = corn gluten meal
```

```
        17 = wheat
        18 = gluten feed
        19 = vegetable oil
        20 = canola meal
$offtext
;

PARAMETERS

* Per hectare crop costs are based on OMAF 2014
        Cc(crp) per hectare cost of crops
        / 1 605
          2 489.8
          3 496.22
          4 473.75
        /

* Upstream feed emissions intensity estimates from Adom et al (2012)
        Upstream(offs)
        / 7   910
          8   850
          9   390
          10  460
          11  460
          12  170
          13  320
          14  330
          15  390
          16  390
          17  430
          18  390
          19  460
          20  548
        /

* Per hectare estimates of soil N2O (Little et al, 2008)
        SoilN2O(crp)  Nitrous oxide emissions for crops 1 through 4
        / 1  4.08
          2  0.343
          3  2.126
          4  0.31
        /
* Rotational constraints
        maxrotn(crp)
        / 1 .75
          2 .5
```

```
          3 .5
          4 .75
        /

        minrotn(crp)
        /1 .1
         2 .1
         3 .1
         4 .15
        /

* Crop Yields, based on OMAF (2014a)
        BaseYield(crp) per hectare annual yield for crops 1 through 4 (in metric tons)
        / 1 41.94
          2 3.06
          3 5.19
          4 5.52
        /
* Nutrient requirements, based on OMAF (2014a)
        Nreq(crp) per hectare N requirement for crops 1 through 4 (in kg)
        / 1 140
          2 0
          3 100
          4 0
        /
        Preq(crp) per hectare P requirement for crops 1 through 4 (in kg)
        / 1 20
          2 20
          3 20
          4 40
        /
        Kreq(crp) per hectare K requirement for crops 1 through 4 (in kg)
        / 1 50
          2 40
          3 40
          4 30
        /
* Crop Prices, based on OMAF (2014b)
        Pcs(allmkt) market price for crops sold (crops 1 through 3) in $ per metric ton of dry matter
        /1 50
         2 435.5
         3 205.7
        /

* Feed prices, based on AAFC (2014)
        Pb(offs) market prices for off farm feed purchases ($ per metric ton of dry matter)
```

```
        /
         7  282
         8  322
         9  250
        10  500
        11  500
        12  85
        13  170
        14  170
        15  250
        16  594
        17  290
        18  218
        19  50
        20  475
        /

*Energy requirements are calculated according to IPCC (2006)
* Energy for maintenance
NEm(h) Net energy requirements for maintenance (Kcal per day)
       /
        1 42
        2 49.7
        3 49.7
        /
* Energy for growth
NEg(h)  Net energy requirements for gain (Kcal per day)
        /
         1 9
         2 0
         3 0
        /
* Energy for lactation
NEl(h) Net energy requirements for lactation
        /
          1 0
          2 76.804
          3 88.620
        /

* Number of animals in each cohort, based on DFO (2012)
Qa(h)  Number of animals in cohort

        /1 50
         2 50
         3 50
```

```
        /
* Protein retained for gain, based on IPCC (2006)
PRgain(h)
        / 1 .05
          2 0
          3 0
        /
* Energy coefficients for farm field work
Efuel(crp)
        / 1 3.29
          2 1.72
          3 1.34
          4 0.81
        /
* Energy coefficients for herbicide production
Eherb(crp)
        / 1 0.0
          2 0.12
          3 0.12
          4 0.24
        /
* Milk yields, Based (loosely) on DFO website
DailyYield(h)
        / 1 0
          2 26
          3 30
        /
;

* Nutrient Properties of feeds, based on NRC 2001
TABLE NutProp(fd,n)
            TDN      CP   DE    ADF    NDF     Ca       P    Limit
         1  0.688  0.088  1.91  0.280  0.450  0.012  0.0026   1.00
         2  0.572  0.174  1.84  0.369  0.466  0.000  0.000   0.00
         3  0.599  0.12   1.43  0.376  0.599  0.000  0.000   0.00
         4  0.567  0.228  1.22  0.352  0.432  0.016  0.0031  1.00
         7  0.795  0.297  1.97  0.197  0.388  0.002  0.0083  0.20
         8  0.785  0.132  0.00  0.146  0.3    0.001  0.004   0.50
         9  0.850  0.094  2.09  0.034  0.095  0.004  0.003   1.00
        10  0.814  0.538  2.21  0.062  0.098  0.040  0.007   0.20
        11  0.885  0.463  2.38  0.104  0.217  0.040  0.0066  0.20
        12  0.547  0.178  1.38  0.395  0.509  0.016  0.0031  0
        13  0.563  0.265  0.00  0.458  0.25   0.006  0.0023  0
        14  0.557  0.128  0.00  0.403  0.607  0.006  0.0029  0
        15  0.850  0.094  2.09  0.034  0.095  0.004  0.003   0
        16  0.844  0.65   2.38  0.082  0.111  0.001  0.006   0.20
```

```
        17  0.866  0.142  1.86  0.044  0.134  0.001  0.0043  0.50
        18  0.741  0.238  1.73  0.121  0.355  0.001  0.01    0.15
        19  1.841  0.000  5.65  0.000  0.000  0.004  0.004   0.03
        20  0.699  0.378  0.00  0.205  0.298  0.006  0.0031  0.10

$ontext
        1 = corn silage
        2 = soybean silage
        3 = wheat silage
        4 = alfalfa
        7 = corn ddgs
        8 = oats
        9 = corn grain
        10 = soybean meal
        11 = soybean meal
        12 = alfalfa hay
        13 = grass
        14 = grass
        15 = corn grain
        16 = corn gluten meal
        17 = wheat
        18 = gluten feed
        19 = vegetable oil
        20 = canola meal
$offtext

SCALARS
* IPCC (2006) value for methane producing capacity
        Bo /.24/
*Based on DFO (2012)
       Pm per hectoliter price of milk /73.5/
* Default value for ash (IPCC, 2006)
       Ash /8/
*Fertilizer prices (OFIMP, 2012; Wilson 2014)
      Pn per kg cost of N fertilizer          /1.78/
      Pp per kg cost of P fertilizer          /2.67/
      Pk per kg cost of K fertilizer          /1.7/
* (Fixed) Farm Characteristics
      At total number of hectares of land available                    /150/
* NMAN3 Software (OMAF)
      ManNcont manure N content /.0043/
      ManPcont manure P content /.001/
      ManKcont manure K content /.0027/
;
```

```
POSITIVE VARIABLES
Qf(h,c) amount of crop c being fed to the animal
*Ration Variables
        GE(h)  gross energy intake
        DMI(h)  dry matter intake
        CP(h)   crude protein intake
        ADF(h)  acid detergent fibre intake
        NDF(h)  neutral detergent fibre intake
        roughage(h) roughage intake
        concentrate(h) concentrate intake
        TDN(h)   total digestible nutrients of ration
        REM(h)   ratio of net energy available in diet for maintenance to digestible energy consumed
        SumCrop  total crop land on farm
        MCF    methane conversion factor
        REG(h) ratio of net energy available in diet for gain to digestible energy consumed
Variable
        DietTDN(h)   total digestible nutrients of ration
        ForageDMI(h)  total forage intake of the animal
        ForageNDF(h)  forage NDF intake of the animal
        Calcium(h)    calcium intake of the animal
        Phosphorous(h) phosphorous intake of the animal

* Objective function variables
Variable Profit
Positive Variables
        Rev total revenue
        Costs total costs
        TotalDairyCosts  define total costs related to dairy operation
        TotalCropCosts define total costs related to crop operation
        FdCosts    define total feed costs
        ManCosts   define total manure management costs
        OthrCosts  define other dairy costs
        CrpCosts    define costs of maintaining crop land
        FertCosts define total costs related to fertilizers
        RegCosts  define regulatory costs

*Manure Variables
        mapp(crp) manure applied specifically on each individual crop
        ManUsed  Total manure used on cropland
        Nexcr(h) N excreted by the animal
        man1  manure produced by heifers
        man2  manure produced by first parity cows
        man3  manure produced by second parity cows
        man total amount of manure produced
```

```
* Land and Nutrient Variables
        A(land) Hectares of land devoted to all possible types of land
        Ac(land) Hectares of land devoted to each crop
        Anc(land) Hectares of land devoted to non crop uses
        tNfert total N fertilizer used
        tPfert total P fertilizer used
        tKfert total K fertilizer used
        Nfert(crp) amount of N fertilizer used on crop c
        Pfert(crp) amount of P fertilizer used on crop c
        Kfert(crp) amount of K fertilizer used on crop c
        Napp(crp)  amount of N required and applied on crop c
        Papp(crp)  amount of P required and applied on crop c
        Kapp(crp)  amount of K required and applied on crop c

*Production Variables
Positive Variable Yield(crp)  crop yield
Variable Qc(crp)        Amount of crops produced
        Qcf(crp)        Amount of crops going to feed
        Qcs(crp)   Amount of crops going to market
        Qofp(offs) Amount of off farm purchases made
        Qofb(offs) Amount of off-farm feed purchased
        Qfd(fd)      Amount of all types of feed
        DailyMilkYield(h) milk yield of the animal
        Qm hectoliters of milk produced

* Greenhouse Gas Variables
PRlactation(h)   protein retained for lactation
Cseq(alf)     C sequestered from alfalfa
VS    volatile solids produced
PI(h) protein intake of the animal


* GHG Emissions
Variable SumSoilN2O sum of soil N2O from crops produced on the farm
EntericCH4 enteric methane emissions
MM    manure methane emissions
MN2O  manure nitrous oxide emissions
tCseq  C sequestration from land use change on the farm
FarmEnergyCO2
USEmissions  upstream emissions from feed production
Ems energy emissions from manure spreading
Emilking  energy emissions from milking
Effw  energy emissions from farm field work
Efah  energy emissions from fertilizer and herbicide manufacturing
Variable TotalGHGs  total GHG emissions
;
```

```
* Declarations of variable bounds (required to avoid divide by zero, and other errors)
DietTDN.l(h) = .001 ;
Qc.l(fdmk) = 100;
man.lo = 3;
REM.lo(h) = .01  ;
REG.lo(h) = .01 ;
DMI.lo(h) = .01;

EQUATIONS
* Objective Function
        Objective define objective function
        Revenue define revenue
        Cost define cost
        TotalDairyCost  define total dairy cost
        TotalCropCost   define total crop cost
        FeedCosts costs for purchasing feed
        ManureManagementCosts define cost of manure management
        OtherDairyCosts  define costs for all other categories of dairy production costs
        CropCosts define costs for maintaining crop land
        FertilizerCosts define costs for purchase of fertilizer
        RegulatoryCosts define fees paid to regulators

* Identities
        CropProduction(crp)  define quantity of crops produced
        MilkProduction define quantity of milk produced
        ManureProduction1(heifers)  define amount of manure produced
        ManureProduction2(firstparity)  define amount of manure produced
        ManureProduction3(secondparity) define amount of manure produced
        TotalManure sum of manure produced on farm
        ManureFate define fate of manure
        ManureExport ensure that manure produced is applied on farm
        FeedFate  define fate of crops produced on farm
        CropLand  define land allocation on the farm
        NonCropLand define land allocation on the farm
        LandFate   set total land allocated to crops to amount of land on the farm
        rotation(crp)  crop rotation constraint
        rotation2(crp) crop rotation constraint 2
        CropFate1(fdmk) define fate of crops used as feed and sold
        CropFate2(alf)      define fate of alfalfa on the farm
        Nrequirements(crp) define N requirements for crops
        Prequirements(crp) define P requirements for crops
        Krequirements(crp) define K requirements for crops
        Napplication(crp)  define amount of N applied
        Papplication(crp)  define amount of P applied from all sources
```

Kapplication(crp) define amount of K applied from all sources
TotalNFertilizer define total N fertilizer used on farm
TotalPFertilizer define total P fertilizer used on farm
TotalKFertilizer define total K fertilizer used on farm
TotalDigestibleNutrients(h) determine TDN of rations
DryMatterIntake(h) determine DMI of the rations
CrudeProteinIntake(h) determine CP of the rations
NeutralDetergentFibreIntake(h) determine NDF of the rations
AcidDetergentFibreIntake(h) determine ADF of the rations
CalciumIntake(h) determine Calcium intake of the rations
PhosphorousIntake(h) determine Phosphorous intake of the rations
ForageIntake(h) determine forage intake of the rations
ForageNDFIntake(h) determine forage NDF intake of the rations
RoughageIntake(h) determine roughage intake of the rations
ConcentrateIntake(h) determine concentrate intake of the rations
EnergyRequirement_Lactating(lact) ensure cows receive required energy
EnergyRequirement_Heifers(heifers) ensure heifers receive required energy
ProteinRequirement2(h) ensure protein requirements
FibreRequirement1(h) ensure fibre requirements
FibreRequirement2(h) ensure fibre requirements
FibreRequirement3(h) ensure fibre requirements
FibreRequirement4(h) ensure fibre requirements
CalciumRequirement(h) ensure calcium requirements
PhosphorousRequirement(h) ensure phosphorous requirements
Limit1(fd,h) upper bounds of feeds in rations
ForageRequirement1(h) ensure forage requirements
ForageRequirement2(h) ensure forage requirements
ForageNDFRequirement(h) ensure forage NDF requirements
NetToDigestibleEnergyMaintenance(h) calculate REM
NetToDigestibleEnergyGain(h) calculate REG
GrossEnergyCalculation(h) calculate GE
TotalEntericMethane calculate enteric methane
VolatileSolids calculate volatile solids
ManureMethane calculate manure methane
ManureFactor define methane conversion factor (MCF)
ProteinIntake(h) determine protein intake
ProteinForLactation(h) determine protein retained for lactation
NExcretion(h) determine N excretion
ManureN2O determine manure nitrous oxide emissions
TotalSoilN2O determine soils N2O from farm soils
CarbonSequestered4 Determine cabon sequestered through land use change on the farm
TotalGHGEmissions Sum of GHG emissions
ManureEmissions Energy related emissions from manure spreading
MilkingEmissions Energy related emissions from milking
FarmFieldWorkEmissions Energy related emissions from farm field work
FertilizerandHerbicideEmissions Energy related emissions from manufacturing of inputs

```
        EnergyEmissions  Sum of energy emissions
        OffFarmEmissions  Upstream emissions from feed production
        EmissionConstraint GHG restriction

;

* OBJECTIVE FUNCTION
Objective                    ..      Profit          =E=  Rev - Costs    ;

Revenue                      ..      Rev             =E=  Qm*Pm +
Sum((allmkt),Qcs(allmkt)*Pcs(allmkt))  ;
Cost                         ..      Costs           =E=  TotalDairyCosts + TotalCropCosts + RegCosts;

TotalDairyCost               ..      TotalDairyCosts   =E=  FdCosts  + OthrCosts ;
TotalCropCost                ..      TotalCropCosts    =E=  CrpCosts + FertCosts + ManCosts ;

FeedCosts                    ..      FdCosts         =E= Sum((offs),Qofb(offs)*Pb(offs));
OtherDairyCosts              ..      OthrCosts       =E= 12.36*Qm    ;
ManureManagementCosts        ..      ManCosts        =E= .00532*ManUsed      ;
CropCosts                    ..      CrpCosts        =E= Sum((crp),Ac(crp)*Cc(crp))    ;
FertilizerCosts              ..      FertCosts       =E= tNfert*Pn + tPfert*Pp + tKfert*Pk    ;
RegulatoryCosts              ..      RegCosts        =E= 0    ;

***  IDENTITIES
* Crop land must sum to total land area
CropLand                     ..      SumCrop         =E=  Sum((crp),Ac(crp)) ;
NonCropLand                  ..      0               =E=  Sum((ncland),Ac(ncland)) ;
LandFate                     ..      At              =E=  SumCrop    ;

* Upper and lower bounds for crop rotation
rotation(crp)                ..      maxrotn(crp)*SumCrop =G= Ac(crp);
rotation2(crp)               ..      minrotn(crp)*SumCrop =L= Ac(crp);

* Production functions for crops, milk, and manure
cropproduction(crp)     ..           Qc(crp)           =E= Ac(crp)*BaseYield(crp) ;
milkproduction          ..           Qm                =E= 7981   ;
ManureProduction1(heifers)          ..  man1              =E= Qa(heifers)*(DMI(heifers)*4.158-
480*.0246)          ;
ManureProduction2(firstparity)      ..  man2              =E= Qa(firstparity)*(DMI(firstparity)*2.63
+ 9.4)          ;
ManureProduction3(secondparity)     ..  man3              =E=
Qa(secondparity)*(DMI(secondparity)*2.63 + 9.4)          ;
TotalManure                         ..  man               =E= (man1 + man2 + man3) ;


* Manure not applied on land is exported
```

```
ManureFate          ..          ManUsed      =E= Sum((crp),mapp(crp)) ;
ManureExport         ..           man - ManUsed =E= 0 ;

* Define fate of crops grown on farm (i.e. to feed or to market)
CropFate1(fdmk)        ..         Qc(fdmk)   =E= Qcs(fdmk) +
(Sum((h),Qa(h)*Qf(h,fdmk)*365)/1000);
CropFate2(alf)        ..         Qc(alf)    =E= Sum((h),Qa(h)*Qf(h,alf)*365)/1000;
FeedFate(offs)        ..         Qofb(offs) =E= Sum((h),Qa(h)*Qf(h,offs)*365)/1000;

* Determine total nutrient requirements
Napplication(crp)       ..     Napp(crp) =E=   Ac(crp)*Nreq(crp) ;
Papplication(crp)       ..     Papp(crp) =E=   Ac(crp)*Preq(crp)  ;
Kapplication(crp)       ..     Kapp(crp) =E=   Ac(crp)*Kreq(crp)  ;

* Determine source of nutrients
Nrequirements(crp)         .. Napp(crp) =E= mapp(crp)*ManNcont +  Nfert(crp) ;
Prequirements(crp)         .. Papp(crp) =E= mapp(crp)*ManPcont +  Pfert(crp) ;
Krequirements(crp)         .. Kapp(crp) =E= mapp(crp)*ManKcont +  Kfert(crp) ;

* Tally the sum of each type of fertilizer required to meet crop nutrients
TotalNFertilizer            ..    tNFert =E= Sum((crp),Nfert(crp)) ;
TotalPFertilizer            ..    tPFert =E= Sum((crp),Pfert(crp)) ;
TotalKFertilizer            ..    tKFert =E= Sum((crp),Kfert(crp)) ;


*** DEFINE NUTRIENT PROPERTIES OF THE RATION
TotalDigestibleNutrients(h)           .. DietTDN(h)     =E=
(Sum((fd),(Qf(h,fd)/DMI(h))*NutProp(fd,"TDN")))*100     ;
DryMatterIntake(h) ..                    DMI(h)         =E=  Sum((fd),Qf(h,fd)) ;
CrudeProteinIntake(h)  ..                CP(h)          =E=  Sum((fd),Qf(h,fd)*NutProp(fd,"CP"));
AcidDetergentFibreIntake(h) ..           ADF(h)         =E=
Sum((fd),Qf(h,fd)*NutProp(fd,"ADF"));
NeutralDetergentFibreIntake(h) ..        NDF(h)         =E=
Sum((fd),Qf(h,fd)*NutProp(fd,"NDF"));
ForageIntake(h) ..                       ForageDMI(h)   =E=  Sum((forage),Qf(h,forage));
ForageNDFIntake(h) ..                    ForageNDF(h)   =E=
Sum((forage),Qf(h,forage)*NutProp(forage,"NDF"));
CalciumIntake(h) ..                      Calcium(h)     =E=  Sum((fd),Qf(h,fd)*NutProp(fd,"Ca"));
PhosphorousIntake(h) ..                  Phosphorous(h)  =E=  Sum((fd),Qf(h,fd)*NutProp(fd,"P"));
RoughageIntake(h)   ..                   roughage(h)    =E=  Sum((rough),Qf(h,rough));
ConcentrateIntake(h) ..                  concentrate(h)  =E=  Sum((conc),Qf(h,conc));

*** DEFINE NUTRIENT REQUIREMENTS FOR ANIMALS
EnergyRequirement_Lactating(lact) ..          (NEm(lact)+ NEg(lact)+ NEl(lact))*.2388459
=E=   DMI(lact)*(.0245*DietTDN(lact)-.12);
```

```
EnergyRequirement_Heifers(heifers) ..           22.5                                    =E=
(.04409*DietTDN(heifers)*1.01 -.45)*DMI(heifers);
ProteinRequirement2(h) ..                    .2*DMI(h)                    =G= CP(h);
FibreRequirement1(h) ..                      DMI(h)*0.17                   =L= ADF(h);
FibreRequirement2(h) ..                      DMI(h)*0.25                   =L= NDF(h);
FibreRequirement3(h) ..                      DMI(h)*0.27                   =G= ADF(h);
FibreRequirement4(h) ..                      DMI(h)*0.35                   =G= NDF(h);
ForageRequirement1(h)       ..               .5*DMI(h)                    =G= ForageDMI(h);
ForageRequirement2(h)       ..               0.2*DMI(h)                    =L= ForageDMI(h);
ForageNDFRequirement(h)     ..                0.20*DMI(h)                    =L= ForageNDF(h);
Limit1(fd,h)  ..                          Qf(h,fd)                       =L= NutProp(fd,"Limit")*DMI(h) ;
CalciumRequirement(h) ..                      Sum(fd,Qf(h,fd)*NutProp(fd,"Ca")) =G= .003*DMI(h)
;
PhosphorousRequirement(h) ..                   Sum(fd,Qf(h,fd)*NutProp(fd,"P"))  =G=
.003*DMI(h) ;

*** EMISSIONS ESTIMATION PROCEDURE  (determined by the ration)

* Enteric Methane
TotalEntericMethane                            ..    EntericCH4/25 =E= (1/55.58)*Sum( (h),
Qa(h)*365*(2.16 + 0.493*DMI(h) - 1.36*ADF(h) + 1.97*NDF(h)));

* Manure Methane
NetToDigestibleEnergyMaintenance(h)              ..    REM(h)     =E=   1.123 -
(0.004092*DietTDN(h)) + (0.00001126*DietTDN(h)*DietTDN(h)) - (25.4/DietTDN(h));
NetTodigestibleEnergyGain(h)                   ..    REG(h)     =E=   1.164 -
(0.005160*DietTDN(h)) + (0.00001308*DietTDN(h)*DietTDN(h)) - (37.4/DietTDN(h));
GrossEnergyCalculation(h)                     ..    GE(h)      =E=   (((NEm(h) + NEl(h))/REM(h)) +
(NEg(h)/REG(h)))*100/DietTDN(h);
VolatileSolids(h)                          ..     VS(h)      =E=   (GE(h)*(1-(DietTDN(h)/100)) +
0.04*GE(h))*.92/18.45 ;
ManureFactor                               ..     MCF        =E=   .18;
ManureMethane                               ..     MM/25      =E=
Sum((h),365*Qa(h)*VS(h)*Bo*MCF*0.67);

* Manure Nitrous Oxide
ProteinIntake(h)                           .. PI(h)          =E= (GE(h)*CP(h)/DMI(h))/18.45;
ProteinForLactation(h)                       .. PRlactation(h) =E= DailyYield(h)*0.035;
NExcretion(h)                              .. Nexcr(h)       =E= (PI(h)/6.25) - (PRlactation(h)/6.38) -
(PRgain(h)/6.25);
ManureN2O                                   .. MN2O/298       =E= 365*Sum((h),Qa(h)*Nexcr(h)*(.005
+ .4*.01)) ;



* Soil Nitrous Oxide (a function of ration)
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* Note: this distinguishes between emissions from crops used in the rations, and those sold
TotalSoilN2O                            ..  SumSoilN2O/298     =E=
Sum((alf),SoilN2O(alf)*Ac(alf)) +
Sum(fdmk,Ac(fdmk)*SoilN2O(fdmk)*((Sum((h),Qa(h)*Qf(h,fdmk)*365)/1000)/Qc(fdmk)))     ;

* Carbon Sequestration from land use change (assumes original land allocation has 15% of
farmland allocated to alfalfa)
CarbonSequestered4          ..   tCseq          =E=
1*(44/12)*10*3691*0.0238*((Sum(seq,Ac(seq))/150)-.15)*150 ;



* GHG Summation
* Energy Emissions
EnergyEmissions                          ..   FarmEnergyCO2       =E=  Ems + Emilking + Effw +
Efah   ;
ManureEmissions                          ..   Ems                =E=  .266*ManUsed*.0248*70 ;
MilkingEmissions                         ..   Emilking           =E=  968*100*.2 ;
FarmFieldWorkEmissions                     ..   Effw               =E=
Sum((crp),Ac(crp)*Efuel(crp))*70 ;
FertilizerandHerbicideEmissions              ..   Efah               =E=
Sum(crp,Eherb(crp)*Ac(crp))*5.8 +  3.59*tNfert + .569*tPfert;

OffFarmEmissions                         ..      USEmissions     =E=
Sum((offs),Upstream(offs)*Sum((h),Qa(h)*Qf(h,offs)*365)/1000);
TotalGHGEmissions                         ..      TotalGHGs       =E=  EntericCH4 + MM + MN2O
+ SumSoilN2O  + USEmissions +  FarmEnergyCO2 - tCseq;
EmissionConstraint                       ..      TotalGHGs       =G=  1  ;

MODEL DAIRYFARM /ALL/;
Solve DAIRYFARM Maximizing Profit using NLP;
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