AN ECONOMIC EVALUATION OF THE EFFECT OF NITROUS OXIDE EMISSIONS PRICING ON CROP FARMERS IN SASKATCHEWAN

A Thesis Submitted to the
College of Graduate and Postdoctoral Studies
In Partial Fulfillment of the Requirements
For the Degree of Master of Science

In the Department of Agriculture and Resource Economics
University of Saskatchewan

By
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The Federal Greenhouse Pollution Pricing Act was implemented in Saskatchewan on April 1, 2019 starting at $20 CAD per tonne of carbon dioxide equivalent (CO$_2$e), increasing by $10$ CAD every year through 2022. The goal of this policy is to reduce GHG emissions by 50-60 million tonnes by 2020. Despite contributing ten percent of nationwide emissions, the agricultural industry is mostly exempt from the policy. To enhance policy efficiency, I consider a policy alternative that covers nitrous oxide emissions from nitrogen fertilizer. I examine the effect of both the federal policy and the optimal Pigouvian tax on Saskatchewan crop farmers’ use of nitrogen fertilizer in this hypothetical scenario. The estimated Pigouvian tax for nitrogen fertilizer use is approximately $268$ CAD per tonne of fertilizer nitrogen. I find a $5\%$ and $9\%$ reduction in nitrogen fertilizer use under the federal policy and the Pigouvian tax, respectively.
Firstly, I would like to express my sincere gratitude to my supervisor Dr. Tristan Skolrud for his invaluable guidance, support, patience, empathy and words of encouragement during the course of this program. To my committee, Dr. Kenneth Belcher and Dr. Richard Gray, I am extremely grateful for their guidance, support and insightful comments. I am grateful to Dr. Tristan Skolrud and Dr. Richard Gray for their financial support during the course of this program. Special thanks to my external examiner, Dr. Emma Stephens for her insightful comments. Finally, I must thank Dr. Mohammad Khakbazan from Agriculture and Agri-Food Canada for his valuable contribution in the completion of this thesis.

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LIST OF ABBREVIATIONS

CEEMA – Canadian Economic and Emissions Model for Agriculture

CO2E – Carbon dioxide Equivalent

CPE – Calibrated Production Equilibrium

GHG – Greenhouse Gas

IAMS – Integrated Assessment Models

IPCC – Intergovernmental Panel on Climate Change

MSB – Marginal Social Benefit

MSC – Marginal Social Cost

N – Nitrogen

UNFCC – United Nations Framework Convention on Climate Change
CHAPTER 1 - INTRODUCTION

1.1 Background

Greenhouse gas (GHG) emissions pricing across different nations has played a significant role in global GHG reduction. However, it is important to recognize the roles of the Kyoto Protocol and the Paris Agreement as the genesis of GHG emissions pricing across countries. The Kyoto Protocol was the first international agreement that legally binds countries to commit to reducing their domestic GHG (United Nations Framework Convention on Climate Change 2008; World Bank 2017). In the Kyoto Protocol, developed countries were obligated to reduce their GHG emissions while there were no requirements for developing countries. The emission reduction commitments of these developed countries varied (United Nations Framework Convention on Climate Change 2008). For example, Canada committed to reduce GHG emissions to 6% below the 1990 levels between 2008 and 2012 (United Nations Framework Convention on Climate Change 2008). There was the Copenhagen Agreement in 2009 followed by the Paris Agreement in 2015. Unlike the Kyoto Protocol, the Paris Agreement requires all countries under the United Nations Framework Convention on Climate Change (UNFCC) to voluntarily commit to their own national emission reduction targets (World Bank 2017). Canada committed to reduce GHG emissions by 30% below 2005 levels by 2030 (Government of Canada 2019).

The Canadian federal government and some individual provinces have created various initiatives to reduce the emission of greenhouse gases. One option is to put a price on GHG emissions which has been shown to be the most cost-effective means of reduction (Pearce 1991; Greenhouse Gas Pollution Pricing Act 2019; Government of Alberta 2019). In the last decade, there has been a rapid increase in GHG emissions pricing initiatives. According to a report by World Bank (2017), GHG emission pricing initiatives have quadrupled in the last decade. This increase includes not only national GHG emission pricing schemes but an increase in the number of companies who are implementing voluntary internal GHG emission pricing. The Canadian
federal government introduced the Pollution Pricing Act on April 1, 2019 (formerly the Pan-Canadian Framework) which is a carbon tax to reduce GHG emissions as part of the commitment to the Paris Agreement.

Agriculture contributes a significant amount to aggregate GHG emissions (Robertson et al. 2000; World Bank Group 2017). Agricultural GHG emissions can be divided into on-farm and off-farm sources in both crop and livestock production. The on-farm and off-farm sources of GHG in crop production or animal production are usually associated with a specific GHG. In crop production, the on-farm sources of GHG emissions are from practices carried out on the farm such as manure and fertilizer application or burning of crop residue. While nitrous oxide is emitted both directly and indirectly in large amounts from nitrogen fertilizer application in crop production1, carbon dioxide is emitted significantly from the burning and the decomposition of carbon residue in the soil under aerobic conditions (Kulshreshtha et al. 1999). Methane is emitted in crop production from decomposition of carbon residue in the soil under anaerobic conditions (Kulshreshtha et al. 1999). The off-farm sources are activities outside of the farm gate (Kulshreshtha et al. 1999). These include production of herbicides, fertilizers and manure. Hence, the major GHG from both on-farm and off-farm sources of GHG emissions in crop production are carbon dioxide and nitrous oxide. The on-farm sources of GHG from animal production is methane from anaerobic digestion of livestock and livestock manure (Kulshreshtha et al. 1999; Government of Canada 2018). The off-farm sources of GHG in animal production include fuel use in livestock processing and packaging plants and is associated with carbon dioxide (Government of Canada 2018). In animal production, the major GHG are carbon dioxide and methane. The implication of these agricultural GHG sources is that modifying one farming practice in a bid to address the reduction of a specific GHG may not necessarily reduce other GHGs (Janzen et al. 2006). For example, reducing the amount of synthetic nitrogen fertilizer would help in reducing total nitrous oxide emitted but may not reduce on-farm carbon dioxide emissions. An understanding of the type of GHG emitted by an agricultural activity guides both farmers and policy makers in their GHG mitigation strategies.

The Agricultural industry accounted for 71% of national nitrous oxide emissions (Government of Canada 2018). Of these amount of agricultural nitrous oxide emissions, the

1 Directly through the process of nitrification and denitrification.
application of synthetic nitrogen fertilizer in the prairie provinces contributed 21% (Government of Canada 2018). Nitrous oxide has a significant climate impact as it is about 300 times the warming potential of carbon dioxide (Del Grosso et al. 2008).

In Canada, farmers have a significant political power and have successfully convinced both the provincial and federal governments to exempt the agricultural industry from the Pollution Pricing Act. Some of the arguments for exempting the agricultural industry are the difficulties in measuring emissions and the competitiveness of the industry (Rivers and Schaufele 2015). With respect to the first problem, the difficulty in measuring emissions, various methods of estimating GHG emissions from the agricultural industry have been developed such as software programs (Agriculture and Agri-Food Canada 2020a), emission coefficients for farming practices (Kulshreshtha et al. 2002) and measuring instruments placed on the farm to estimate GHG emissions (Agriculture and Agri-Food Canada 2020b). Examples of models developed for estimating GHGs include HOLOS and Canadian Economic Emissions Model for Agriculture (CEEMA) (Kulshreshtha et al. 2002; Agriculture and Agri-Food Canada 2020a). HOLOS and CEEMA are both used in estimating the GHG emissions covered in this research and would be described in detail in a later section. These two methods have been available prior to the time these emission reduction policies were implemented. This research estimates and contrasts the nitrous oxide emissions from the application of nitrogen fertilizer using CEEMA, HOLOS, and IPCC frameworks. On the second reason of exempting the agricultural industry, various studies have examined the effect of a carbon tax on the competitiveness of farmers. Rivers and Schaufele (2015) examine the effect of British Columbia’s revenue neutral carbon tax and finds little evidence that the competitiveness of farmers is reduced. However, this conclusion should not exclude the possibility that farmers may be negatively impacted by a carbon pricing policy. This is because the outcome of a GHG pricing policy varies depending on the circumstance (Fullerton and Metcalf 1997). For example, Slade (2018) examined the effect of pricing Canadian livestock emissions and finds a reduction in producer surplus if a carbon tax is applied at the producer level. Additional studies, (Liang, Lovejoy and Lee 1998; Aldy and Pizer 2012; Carbone and

2 A software program by Agriculture and Agri-Food Canada that estimates GHG emissions based on information entered for an individual farm.

3 These two methods may be costly and involve treating farms differently due to varying biophysical characteristics on each of the farms (Garnache et al. 2017).
Rivers 2017) that examined the effect of an environmental policy on the competitiveness of sectors and social welfare find a reduction in GHG emissions and a negative impact on the competitiveness of the sectors affected.

1.2 Problem Statement

The Federal Greenhouse Gas Pollution Pricing Act and provincial GHG emissions pricing policies have mostly exempted the agricultural industry from their GHG emissions pricing policies\(^4\) (Government of British Columbia 2008; Ali 2015; Greenhouse Gas Pollution Pricing Act 2019; Government of Alberta 2019). Considering the significant amount of GHG emissions from the agricultural industry and the recognition of the agricultural industry as a significant sink for atmospheric carbon (Government of Canada 2018), with the development of an appropriate policy, agriculture may play an important role to make the emission reduction goal more feasible (Samarawickrema and Belcher 2005).

1.3 Motivation for the Research


In order for the GHG reduction emission goal to be efficient, all GHG producing sectors in the economy would have to be covered under the Greenhouse Gas Pollution Pricing Act (Baumol and Oates 1988). Currently, all GHG producing sectors are not covered under the Greenhouse Pollution Pricing Act. According to Metcalf (2007) and Kolstad (2011), a well-designed GHG emission pricing policy should be efficient and cost-effective. An efficient emissions pricing policy equates the marginal damage of the GHG emissions to the marginal cost

\(^4\) The provinces with an emission pricing policy in place include Alberta, British Columbia, Ontario and Quebec. British Columbia did not exempt the agricultural industry at the onset of its carbon tax (Government of British Columbia 2008).
of control (Kolstad 2011). A cost-effective emissions pricing policy has been shown to be the cheapest means of reducing a given amount of GHG emissions (Kolstad 2011). The Greenhouse Gas Pollution Pricing Act does not meet the conditions for a well-designed GHG emissions pricing policy. An efficient Greenhouse Gas Pollution Pricing Act would cover GHG emissions from the agricultural industry.

1.4 Scope of the Study

This research only covers the on-farm sources of GHG emissions in crop production specifically nitrogen fertilizer applied to the soil for crop production because nitrogen fertilizer is less costly to monitor than the other sources of farm-level GHG emissions. Hence, nitrous oxide is the only gas covered. The nitrous oxide emissions considered in this research are expressed in Carbon dioxide Equivalent (CO$_2$e). This research does not cover the following:

- GHG emissions from the manufacture, transportation, and on-farm storage of farm inputs such as fertilizers and manures.
- GHG emissions from the transportation of farm products from the farm to the next stage of the supply chain.

1.5 Objectives

This research aims to evaluate an emissions reduction approach for the agricultural industry, specifically nitrous oxide emissions tax on nitrogen fertilizer used in crop production. The specific objectives of the study include:

- To calculate the optimal Pigouvian tax rate for nitrogen fertilizer used in crop production in Saskatchewan.
- To estimate the effect of a nitrous oxide emissions tax on crop farmers’ emissions and input use in the following scenarios:
  - The Greenhouse Gas Pollution Pricing Act

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5 This comprises major crops like spring wheat, canola and lentils.
6 These inputs are produced in plants powered by fossil fuels, natural gas that give off GHG emissions. That is, the production process of these agricultural input generates GHG in addition to the on-farm direct emissions from using these inputs, these types of emissions are called second-round emissions and are difficult to measure (Kulshreshtha et al. 1999).
1.6 Rationale

The current federal GHG Pollution Pricing Act in Canada is not set equal to the estimated social costs of carbon. In addition, the federal carbon taxes do not cover all sectors that produce GHG for example, the agricultural industry. Hence the GHG emission pricing policy is inefficient. This research addresses this problem by estimating a Pigouvian tax for nitrogen fertilizer use in crop production for Saskatchewan farmers.

There is a mixed opinion about the effect of a GHG emission pricing on farmers as a good move to address climate change with farmers being negatively impacted. There are divided conclusions from literature on the effect of a GHG emission tax on farmers. This research analyzes the effect of nitrous oxide emissions tax on farmers in Saskatchewan and contributes to one school of thought on the effect of a tax on welfare and its effectiveness in addressing climate change.

1.7 Thesis Organization

This thesis proceeds with a review of literature on GHG emissions and sinks from the Canadian agricultural industry in Chapter 2. Chapter 2 discusses fertilizer management and use in Canada, models that have been developed to estimate GHG emissions from the agricultural industry. Also, Chapter 2 covers the social costs of carbon and the carbon pricing initiatives adopted by various governments around the world to reduce GHG emissions. Chapter 3 presents the theoretical framework and proceeds with an overview of the model developed to reduce GHG emissions, this model is comprised of both the farmers’ problem and the government’s problem. Chapter 3 also covers the mechanism of a Pigouvian tax and the calibration of the production function. Chapter 4 presents the methods followed in order to achieve the objectives of this research. These methods include an explanation on how the nitrous oxide emissions are estimated, the soil zones of the study area and a summary of the data used in calibrating the farmers’ production function. Chapter 5 is the results and discussion. This chapter presents the outcome of the analysis and discusses these results. Chapter 6 is the conclusion and it also includes the contribution of this research to previous literature, limitations and future research.
CHAPTER 2 - LITERATURE REVIEW

2.1 Chapter Introduction

Chapter 2 provides an overview of literature on GHG in the agricultural industry. First is a review of GHG emissions and sink in the agricultural sector. This chapter proceeds with fertilizer management in the agricultural sector, models for estimating GHG emissions from agriculture, the social costs or carbon and lastly GHG emissions pricing in the agricultural industry.

2.2 GHG Emissions and Sinks in the Agricultural Sector

Farming practices can contribute emissions to the atmosphere, while also certain practices result in sequestration of carbon and carbon sinks. Emitters add carbon dioxide to the atmosphere. Sinks remove carbon from the atmosphere. It is not unusual that a farming practice can be both an emitter and a sink. In this case, the emission and sink are added to obtain the net emissions of the farming practice. A positive net emission is an emitter and a negative net emission is a sink. Sources of GHG emissions and sinks in agriculture are discussed below:

2.3 Emissions

GHG emissions from the agricultural industry are mostly from biological processes.\(^7\) (Canada – National Inventory Report 2016). Some of the other sources of GHG emissions from the agricultural industry includes manure application, crop residue decomposition, the application of synthetic nitrogen fertilizers and fossil fuel combustion for various farming activities such as seeding, harvesting, grain drying and transport (Government of Canada 2018; Agriculture and Agri-Food Canada 2020b). In 2009, Agriculture and Agri-Food Canada

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\(^7\) Enteric fermentation accounted for 41\% of total agricultural GHG emissions (Canada - National Inventory Report 1990-2016 part 1)

\(^8\) Accounted for 22\% of total agricultural GHG emissions (Canada - National Inventory Report 1990-2016 part 1)
estimated that Canada produced 690 million tonnes of GHG with agriculture contributing 10% to these emissions (Agriculture and Agri-Food Canada 2020b). As of 2016, the province of Saskatchewan was the third largest contributor of GHG emissions in Canada (Government of Canada 2018) Agricultural emissions contributed 23% of the 75.5 million tonnes of GHG from Saskatchewan (Government of Canada 2020). According to Agricultural and Agri-Food Canada (2014), agricultural sources of GHG emissions can be classified into on- and off-farm. These sources are shown in Figure 2.1:

Source: Agriculture and Agri-Food Canada 2020b.

**Figure 2.1. Sources of GHG Emission from the Agricultural Industry**

Figure 2.1 shows both the off-farm and on-farm sources of GHG emissions. The off-farm sources include leaching and volatilization, electrical and energy production, manufacturing of fertilizer, pesticide and farm machinery. The on-farm sources of GHG emissions include fossil fuel combustion, manure application and storage, fertilizer application, pesticide application, crop residue decomposition and enteric fermentation. The GHG emissions covered in this study fall

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9 The agricultural industry is the second major emitter after the oil and gas industry with 34% (Government of Saskatchewan 2014)
into the on-farm sources of GHG emissions, specifically emissions from nitrogen fertilizer applied to the soil for crop production.

Emissions from nitrogen fertilizer can be classified into direct and indirect emissions (Intergovernmental Panel on Climate Change [IPCC] 2006a). Addition of nitrogen fertilizer to the soil increases the amount of nitrogen available in the soil (IPCC 2006a). Direct emissions are produced directly from the soil through the process of denitrification and nitrification (IPCC 2006a). Indirect emissions are through leaching, volatilization, runoff and biomass (Bouwman 1990, Butterbach-Bahl et al. 2013).

2.3.1 Sinks

Sinks are natural reservoirs that absorb carbon from the atmosphere through the process of carbon sequestration. Sinks can also be referred to as carbon stocks while carbon sequestration is the process of transferring carbon dioxide from the atmosphere to the soil through plant residues, plants and are stored in the unit as part of the organic matter (Olson 2014). Important examples of carbon sinks include forests and soils10. Soil organic matter contributes to the productivity of the soil. This is because soil organic matter contributes to the ability of the soil to provide nutrients and moisture to crops thereby increasing crop yield. Higher crop yields imply an increased rate of carbon dioxide capture from the atmosphere (Kulshreshtha et al. 1999). The common farming practices to increase soil organic matter in Western Canada include the use of cover crops and zero tillage (Kulshreshtha et al. 1999; Awada et al. 2016).

2.3.2 Net Emissions

Net emissions are calculated by considering both emissions and sinks. There is an emissions’ trend for the agricultural industry. The agricultural industry in Canada moved from a net source of GHG in 1990 to a net sink of GHG in 2002 and back to being a net source in 2018 (Environment Canada 2004; Environment Canada 2016). According to Environment Canada (2016), the application of nitrogen fertilizer has increased over the years and is one of the main drivers of the agricultural emissions trend.

10 Forestland (-11 Mt CO2 E), Cropland (-150Mt CO2 E). Agricultural soils are classified under emissions (See Table S-2 in Canada -National Inventory Report 1990-2016 part 1)
2.4 Fertilizer Management and Use in Canada

The GHG emission from fertilizer management and use is unavoidable however the inefficient management and use of fertilizer increases the amount of GHG emitted from fertilizer (Fertilizer Canada 2018). This management of fertilizer includes the method of storage and transportation of fertilizer, time of the year that fertilizer is applied to the soil, method of application (Fertilizer Canada 2018). For example, farmers can reduce GHG emissions by about 20% if nitrogen fertilizers are applied in the spring as opposed to the fall (Fertilizer Canada 2018).

Apart from an emissions tax as an instrument to encourage efficient fertilizer management, the federal government set up the 4R Nutrient Stewardship with the objective of informing farmers on how to use fertilizer from the right source at the right rate, right time and the right place (Fertilizer Canada 2018). That is, farmers are educated on applying the right quantity of fertilizer at the appropriate time of the year and the method of application that minimizes GHG emissions from fertilizer use. With this initiative in place, farmers are encouraged to increase their profitability through higher yields while also ensuring a sustainable environment. By adopting Beneficial Management Practices (BMP) with regards to fertilizer use, farmers can reduce GHG emissions from the farm and leaching of nutrients (Fertilizer Canada 2018).

2.5 Models for Estimating GHG Emissions

The Intergovernmental Panel on Climate Change (IPCC) provides a standard method to estimate GHG emissions (2006a). Studies have shown that the use of IPCC method may be inaccurate (Brown et al. 2001; Flynn et al. 2005). Hence, various region-specific models have been developed to estimate GHG emissions in order to provide more accurate estimates of GHG. Some of these methodologies are based on numerical modeling (Brown et al. 2002; Butterbach-Bahl et al. 2004; Kesik et al. 2005; Britz and Leip 2009) or empirical modeling (Bouwman et al. 2002a b; Lu et al. 2006; Rochette et al. 2008; Dechow and Freibauer 2011). Of these models, some have been developed for Canada (Rochette et al. 2008; Agriculture and Agri-Food Canada. 2020) and specifically for Saskatchewan which is the study area (Kulshreshtha et al. 1999a, Kulshreshtha et al. 2002).
2.6 The Social Costs of Carbon

The social cost of carbon is disutility to consumers from GHG emissions. The social costs of carbon can be defined as the net present value of the incremental damage due to a small increase in the atmospheric stock of carbon dioxide (Tol 2008). In other words, the monetary value of the effect of one more unit of GHG emissions on the climate and the society. Society in this case refers to the world at large. This is because it does not matter where the GHG emission is produced, it stays in the global atmosphere for several years contributing to climate change (IPCC 2013). In other words, climate change involves a global externality (United States Government 2016). The effect of climate change such as rising sea levels and heat waves is felt across globe (Mitchell 1989). Various studies have estimated the social cost of carbon and are damage estimates restricted to a country (World Bank Group 2016; United States Government 2016; Government of Canada 2016; World Bank Group 2017). As stated earlier, an efficient tax is one that is set equal to the social costs of carbon. However, to address the global externality problem of climate change, the social cost of carbon must incorporate the global damage caused by GHG (United States Government 2016). When all countries adopt an emission reduction policy that is consistent with a global estimate of the social cost of carbon, it supports a mutually beneficial approach to achieving an emission reduction and it removes issues such as a country being solely liable for the world’s damage (Pfizer et al. 2014; United States Government 2016).

This research calculates the optimal Pigouvian tax using the social costs of CO\(_2\)e that are damage estimates restricted to Canada (Government of Canada 2016). The estimated social costs for Canada are presented in Table 2.1:
The Government of Canada adopts the United States estimates of the social costs of carbon however Canada only considers two of the estimates (Government of Canada 2016). The two estimates the Government of Canada adopt include the 3% discount rate and the high impact discount rate estimates (Government of Canada 2016). The high impact discount rate represents lower-probability social costs of carbon that are harmful to the society. I will be using the 2016 central rate estimates of the social costs of CO₂e in this study.

The United States estimate of the social costs of carbon is an average of the estimates from the three Integrated Assessment Models (IAMS) (United States Government 2016). In order to account for uncertainty with regards to discounting the future costs, the United States

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Source: Adapted from Government of Canada 2016

All estimates are in 2012 CAD
develops four estimates of the social costs of carbon using four different discount rates (United States Government 2016). These discount rates are 2.5%, 3%, and 5% as the high impact discount rate (United States Government 2016). The United States government defines 3% as the “Central Rate”, in other words, the discount rate to be used for policy making (United States Government 2016). There are two estimates of the social costs of carbon in both 2010 and 2016 due to updates to the earlier versions of all three IAMS. The estimates in the two different years are estimated with the same assumptions on the discount rate, emissions scenarios and climate sensitivity (United States Government 2016). However, the 2016 estimates captures the improved insights from scientific and economic research and this overall effects of the updates is reflected in the relatively higher values of the 2016 estimates in addition to the increase in accumulated stocks of CO₂E (United States Government 2016). As shown in Table 2.1 above, the 2016 estimates of the social costs of carbon are relatively higher than the 2010 estimates.

2.7 GHG Emissions Pricing in Agriculture

The GHG emissions pricing-based approaches to a reduction of GHG emissions most commonly used include taxes, subsidies, and cap-and-trade. A carbon tax is a charge on the emitters of GHG emissions to modify their production to produce GHG emissions at a socially optimum level. With an economically efficient carbon tax, the marginal social cost (MSC) of GHG emissions is equal to the marginal social benefit (MSB). The carbon tax is considered to be one of the simplest approaches to GHG emissions pricing (Rivers and Schaufele 2015; Government of British Columbia 2018). In Canada, the provinces that had carbon tax includes British Columbia, Quebec and Alberta until April 1, 2019 when The Federal Greenhouse Gas Pollution Pricing Act (formerly the Pan-Canadian Framework) came into effect and has now included Saskatchewan, Manitoba, Ontario and New Brunswick (Government of British Columbia 2018; Greenhouse Gas Pollution Pricing Act 2019). A carbon tax set to increase over time like The Federal Greenhouse Gas Pollution Pricing Act is to reflect the increase in the damage as more GHG emissions accumulate in the atmosphere (World Bank 2016).

12 The Federal Greenhouse Gas Pollution Pricing Act is the Government of Canada’s national GHG emission reduction plan.
Alberta applies a carbon levy to diesel, natural gas, gasoline, and propane and (Government of Alberta 2019). In Alberta, agriculture is the only economic sector partially exempted from a carbon tax (Government of Alberta 2019). This exemption includes diesel or gasoline used in carrying out farming operations.

British Columbia included the agricultural industry at the onset of its carbon tax in 2008 until 2014 when the agricultural industry was exempted (Government of British Columbia 2018). In Ontario and Quebec, farmers are not charged for emissions from biological processes, for example GHG emissions from livestock digestion, but farm fuels are not exempted from the fuel tax (World Bank 2016). Outside of Canada, carbon pricing policies have also been favourable to the agricultural sector. In New Zealand, the agricultural industry faces a lower price for carbon relative to other sectors (Aldy and Stavins 2012). The carbon tax in Norway exempts the agricultural industry and the oil and gas sector partially (Bruvoll and Larsen 2004).

As a policy substitute to a carbon tax, a cap-and-trade policy allocates tradable emission allowances equal to an overall cap. The firms within the industry are allowed to trade their allowances. In Canada, Québec and Ontario have adopted a cap-and-trade to reduce their provincial GHG emissions (Government of Canada 2018). The size of an emission cap is decided upon by policy makers (Kolstad 2011). An advantage of cap-and-trade is that the traded allowances can be put to their highest-valued use (Aldy and Stavins 2012). A disadvantage is its administrative complexity. In designing a cap-and-trade, policy makers must decide on the amount of allowance, coverage, and the mode of distributing the allowances (Aldy and Stavins 2012).

Another common climate change policy is subsidies which involve payments to encourage the adoption of practices with zero or low GHG emissions (Kolstad 2011). In Canada for example, Alberta reinvests its tax revenue in the economy by providing funds to support GHG mitigation efforts and tax rebates to individuals and businesses (Government of Alberta 2019). A subsidy may be effective in reducing GHG emissions, however a disadvantage of a subsidy is that it increases aggregate industry emissions while reducing individual firm’s emissions (Baumol and Oates 1988).

GHG emissions pricing in Canadian provinces and some other countries partially or fully exempt the agricultural industry. Agriculture is exempt from a GHG emissions pricing policy in these places for various reasons. In Canada, agriculture is exempted from the carbon tax due to its potential to reduce the competitiveness and profitability of farmers (Government of British Columbia 2008; Rivers and Schaufele 2014). Another explanation that has not been established for the exemption of the agricultural industry from a GHG emission pricing in different regions is due to the difficulty in measuring emissions from the agricultural industry. For example, a Pigouvian tax or subsidy is optimal if the tax amount equals the marginal social cost of GHG emissions. An accurate measurement of GHG is important in order to estimate the damage to the environment from GHG. The third reason is fairness to farmers. The industry provides food to society and whether the industry should be taxed often seem unjust to farmers (Rivers and Schaufele 2015). According to Slade (2018), considering the amount of emissions from the Canadian agricultural industry, it is unlikely that Canada would be able to achieve its long-term emissions reduction target without significant contribution from the industry.

One of the approaches is to reward crop farmers for reducing GHG emissions on their farms. Horowitz and Just (2013) develop a model that simulates rewards to crop farmers for reducing GHG emissions. In their model, the economy is subject to a cap-and-trade policy, but farmers are exempt from the cap, which is similar to the current policy in Alberta (Government of Alberta 2019). However, farmers earn offset credits for emitting GHGs below an endogenous baseline. The farmers can then sell these offsets to emitters in another industry covered by a cap-and-trade. Studies on using incentives for GHG mitigation in the energy industry have shown that it may result in an increase in consumer fuel consumption which in turn results in higher GHG emissions (Galinato and Yoder 2010). The same idea can be applied to the agricultural industry. Both agricultural GHG sources and motor vehicles emissions are a non-point source, the externality from motor vehicles cannot be easily measured at the source and that is a similar characteristic to the agricultural GHG sources (Garnache et al. 2017).

Another policy approach in the agricultural industry is to penalize crop farmers for the emission of GHG. For example, Galinato and Yoder (2010) propose a Pigouvian tax on high carbon energy sources in both the motor fuels and electric power industries. In addition, the revenue from the Pigouvian tax is used to fund subsidies on low carbon energy sources in both industries (Galinato and Yoder 2010). Other studies that suggest penalizing GHG emissions
include Liang et al. 1998; Galinato and Yoder 2010; Skolrud and Galinato 2017. This research follows the approach that penalizes crop farmers for emitting GHGs.

Whether farmers are rewarded or penalized for their management of GHG emissions, both approaches are faced with similar challenges. The first is that the emissions estimated are based on emission coefficients as opposed to direct measurement of emissions, the second is that agricultural GHG emissions occur from many sources with varying emission generation processes (Garnache et al. 2017)

2.8 Chapter Summary

Chapter 2 covered the classification of farming practices into either emitters or sinks, fertilizer management and use in the agricultural industry. A review of literature shows that nitrogen fertilizer use is one of the major contributors of nitrous oxide emissions to national agricultural emissions. In spite of the difficulty in estimating GHG emissions, various region-specific numerical and empirical models have been developed to estimate GHG emissions from the agricultural industry. This chapter also discussed the social costs of carbon and emissions pricing in the agricultural industry.
CHAPTER 3 - THEORETICAL FRAMEWORK

3.1 Chapter Introduction

The review of literature indicates that in Canada the use of nitrogen fertilizer has increased over the years. The agricultural industry is often exempted from emission pricing policies in Canada and some other countries due to the difficulty in estimating GHG emissions. Given the significant amount of emissions from the Canadian agricultural industry, the development of an appropriate emission pricing policy for the agricultural industry may help Canada achieve her GHG emissions reduction target. This chapter sets up a model that is used to evaluate emissions reduction policy for nitrogen fertilizer use on farms in Saskatchewan. The model is comprised of the social planner or government’s problem and the farmer’s problem. This chapter also provides an explanation of how a Pigouvian tax works and the effect of a Pigouvian tax on Saskatchewan crop farmers.

3.2 Model Overview

The model developed in this research is designed specifically for the case of nitrogen fertilizer application rates on crop lands in Saskatchewan, however the intuition of this research can guide taxes for other farming practices such as manure use that also emits GHG in crop production. In this model, the farming practice, which is nitrogen fertilizer use on the farm that determines GHG emissions is observable. The farmer’s production is a function of nitrogen fertilizer applied on the farm. Each unit of nitrogen fertilizer used on the farm emits nitrous oxide emissions once applied to crops on the farm. The nitrous oxide emissions are estimated using three GHG estimation models. The first two models, CEEMA and IPCC involves multiplying the quantity of fertilizer applied by the emission coefficients already determined by each of the GHG estimation models (Kulshreshtha et al. 1999 ; IPCC 2006a). The third estimation, HOLOS requires entering information on the quantity of nitrogen fertilizer and other input quantities applied on the farm. I use the model to evaluate a Pigouvian tax policy for crop farmers in
Saskatchewan. This paper contributes to the existing literature by using a regionalized calibrated production equilibrium (CPE) model for crop production in Saskatchewan following the method of Howitt (1995). This method involves calibrating a constant elasticity of substitution (CES) production function using regional production data. The proposed model is divided into the farmer’s and government’s problem. The government’s problem is presented first:

3.2.1 Government’s Problem

The government sets a Pigouvian tax in order to maximize social welfare. The mechanism of a Pigouvian tax is shown in the graph (Figure 3.1) below:

![Figure 3.1. Mechanism of a Pigouvian Tax](image)

A crop farmer produces at the level in which quantity of GHG emissions is $Q$. At this level, the costs of the crop farmer which is the marginal private cost (MPC) do not include the cost of emissions that are a by-product of using nitrogen fertilizer. These costs are borne by the consumers (society) in the form of environmental damage. The government then introduces the Pigouvian tax, where the magnitude of the tax is equal to the external costs imposed, so that crop farmers bear the costs of emissions at the new output quantity $Q^*$, a lower quantity than the previous quantity.
The farmer cultivates crops that contributes to the welfare of consumers. The farmer makes use of nitrogen fertilizer in the course of crop production resulting in the emission of GHGs. The total emissions from nitrogen fertilizer used during crop production depends on the total quantity of nitrogen fertilizer used on the crop farm:

\[ E = eX^* \]  
(3.1)

Where \( e \) is the emission coefficient per kg of nitrogen fertilizer and \( X^* \) is the total quantity of nitrogen fertilizer used on the farm. These emissions represent an externality on society and a reduction in social welfare. In the model, the aim of the government is to maximize social welfare. As a result, the government sets a Pigouvian tax \( t^* \) to internalize the costs of GHG emissions on consumers.

The social welfare function is given by:

\[ W = U(G) - \delta \]  
(3.2)

Where \( U(G) \) is a concave utility function representing the satisfaction, consumers derive from the crops that farmers cultivate. The dissatisfaction of consumers from each unit of GHG emissions is represented by \( \delta \) and can also be referred to as the social cost of GHG emissions (E). That is, the marginal damage from GHG emissions. The marginal damage of GHG emissions from nitrogen fertilizer on consumers is represented by \( \delta E \). For example, if \( E \) is estimated as the total amount of emissions from one kg of nitrogen fertilizer, \( \delta E \) can be interpreted to be the damage to the society when the farmer uses one more kg of nitrogen fertilizer on the farm\(^{14} \). In order words, marginal damage per kg of nitrogen fertilizer.

The farmers’ revenue is represented below:

\(^{14} \) In this case, the total quantity of nitrogen fertilizer \( X^* \) equals 1.
\[ R = pQ - (r + t^*)X^* - wY^* \]  \hspace{1cm} (3.3)

The value of production, \( G \) in the crop industry is a summation of the farmers’ revenue and the tax revenue:

\[ G = \sum (pQ - (r + t^*) X^* - wY^* + \sum t^* X^* \]  \hspace{1cm} (3.4)

The government sets a Pigouvian tax, \( t^* \) to maximize social welfare:

\[
\max_{t^*} W = U(G) - \delta E
\]  \hspace{1cm} (3.5)

The first-order condition is:

\[
\frac{\partial W}{\partial t^*} = U'(G) \left( \frac{\partial R}{\partial t^*} + X^* + t^* \frac{\partial X^*}{\partial t^*} \right) - \delta \left( e \frac{\partial X^*}{\partial t^*} \right) = 0
\]  \hspace{1cm} (3.6)

Solving for \( t^* \) to yield the marginal damage from GHG emitted per unit of nitrogen fertilizer:

\[
t^* = \frac{\delta e}{U'(G)}
\]  \hspace{1cm} (3.7)

The Pigouvian tax is \( t^* \) and is equal to the marginal damage from each unit of nitrogen fertilizer used in crop production. With the Pigouvian tax in place, the additional costs in the form of social damage are now borne by the crop farmer and these costs are considered in the optimal quantity of inputs for crop production.

\[15\] See Appendix A for how \( t^* \) is derived.
3.2.2 Input Substitution

When the price of an input changes, the farmer alters the input mix in order to minimize production costs. The response of the farmer to an input price change depends on the substitutability of inputs. The substitution between inputs can be examined using the elasticity of substitution. The elasticity of substitution is a measure of how easy it is to replace an input for another input in production. The higher the elasticity of substitution between nitrogen fertilizer and other inputs, the easier it is for the farmer to substitute other inputs for nitrogen fertilizer when the price of nitrogen fertilizer increases from a tax. The lower the elasticity of substitution between nitrogen fertilizer and other inputs, the more difficult it is to substitute other inputs for nitrogen fertilizer when the price of nitrogen fertilizer increases from a tax.

3.2.3 The Effect of a Tax on Crop Farmers

The Federal Pollution Pricing Act and the optimal Pigouvian tax estimated in this research if applied to nitrogen fertilizer used in crop production has an effect on crop farmers. In order for a crop farmer to still minimize costs in addition to the new costs from a tax, the farmer considers two different ways to maximize profits from production.

Firstly, the farmer may decide to reduce quantities of nitrogen fertilizer demanded and use more of the other input with a lower price while still maintaining the same level of output. This is called the substitution effect of a change in input price and output is held constant. The input substitution effect is described in Figure 3.2 on the next page:
Figure 3.2. The Substitution Effect of an Input Price Change

In Figure 3.2, the farmer is originally at point $A$ with input demands $X_1$ and $Y_1$. When the price of nitrogen fertilizer increases due to a tax, the substitution effect of an increase in the price of nitrogen fertilizer causes the farmer to move along the isoquant $Q_1$ to point $B$ with more of other inputs $Y_2$ and less of nitrogen fertilizer $X_2$ because output is held constant. In the case of nitrogen fertilizer, the farmer considers cheaper alternatives to nitrogen fertilizer such as including more nitrogen fixing plants in crop rotation and use of manures.

The effect of a tax on farmers vary across crops depending on the level of importance of nitrogen fertilizer to the production of the crop. For crops like Canola and corn that require large quantities of nitrogen, one would expect the farmer to be less responsive to a higher price of nitrogen fertilizer due to a tax. The demand for nitrogen fertilizer is price inelastic. Other crops like lentils and soybeans require small quantities of nitrogen fertilizer and not including nitrogen...
fertilizer may have little or no effect on the yield, the farmer is more responsive to a higher price of nitrogen fertilizer due to a tax. The demand for nitrogen fertilizer is price elastic. In the case of nitrogen fertilizer, the farmer considers cheaper alternatives to nitrogen fertilizer such as including more nitrogen fixing plants in crop rotation and use of manures.\textsuperscript{16}

3.2.4 Farmer’s Problem

The farmer’s problem is to minimize the cost of producing output conditional on exogenous input prices. The farmer’s aim is to minimize costs subject to the tax levied on the input that emits GHG emissions. Let the farmer’s production function be represented by \( Q = f(X, Y) \) where \( Q \) is output quantity, \( X \) is nitrogen fertilizer and \( Y \) is all other inputs.\textsuperscript{17} The cost function of a farmer that is subject to any form of tax imposed on nitrogen fertilizer is represented below:

\[
C = (r + t)X + wY
\]  

(3.8)

Where \( C \) is the total cost of production is, \( w \) is an index of all other input prices and \( r \) is the price of nitrogen fertilizer. The farmer aims to minimize the total cost of production subject to the tax levied on the input that emits GHG emissions, in this case nitrogen fertilizer. The output constraint of the farmer is given by:

\[
Q = f(X, Y) = Q_0
\]  

(3.9)

The new price of nitrogen fertilizer with the Pigouvian tax is used to solve the farmer’s cost minimization problem, the objective function is formed:

\textsuperscript{16} While the tax may result in a decrease in fertilizer N, the farmer may result to other means to maintain soil N levels in the case of higher tax rates. The outcome as to whether nitrous oxide emissions increases or decreases depends on the practice adopted by the farmer to maintain soil N level and also the soil conditions (nitrous oxide emissions through nitrification and denitrification increases in wet soil conditions). The level of emissions tax considered in this research is likely not large enough to induce changes to the crop mix such as including more nitrogen-fixing plants. The theoretical model used does not account for changes to the crop mix which is one of the limitations of this study.

\textsuperscript{17} All inputs of the farmer other than nitrogen fertilizer are grouped together as one input.
\[ \mathcal{L} = (r + t)X + wY + \lambda(Q_0 - f(X, Y)) \] (3.10)

Solving the objective function yields the first-order conditions:

\[ \frac{\partial \mathcal{L}}{\partial X} = r + t - \lambda \left( \frac{\partial f}{\partial X} \right) = 0 \] (3.11)

\[ \frac{\partial \mathcal{L}}{\partial Y} = w - \lambda \left( \frac{\partial f}{\partial Y} \right) = 0 \] (3.12)

\[ \frac{\partial \mathcal{L}}{\partial \lambda} = Q_0 - f(X, Y) = 0 \] (3.13)

The first order conditions (3.11) and (3.12) can be rearranged such that:

\[ \frac{f_X}{r + t} = \frac{f_Y}{w} \] (3.14)

Invert the fractions in (3.14) to obtain the shadow price of nitrogen fertilizer and other inputs as shown below:

\[ \frac{r + t}{f_X} = \frac{w}{f_Y} = \lambda \] (3.15)

where \( f_X \equiv \frac{\partial f}{\partial X} \) and \( f_Y \equiv \frac{\partial f}{\partial Y} \).
The three first-order conditions as represented by (3.11), (3.12) and (3.13) all need to be met in order for the farmer to minimize costs. The first condition (3.11) implies that the marginal product of nitrogen fertilizer is equal to the price of nitrogen fertilizer and the Pigouvian tax. The second condition (3.12) implies that the value of the marginal product of other inputs equal the input price of other input. The third condition (3.13) indicate that when the farmer’s cost is minimized, the farmer would have spent his available resources on only nitrogen fertilizer and all other inputs. Based on (3.14), this condition implies that for the farmer to minimize cost, the marginal product per dollar spent is the same for nitrogen fertilizer and other inputs. In order to still minimize costs, if the tax imposed increases the cost of the marginal productivity of nitrogen fertilizer, the farmer uses more of other inputs with relatively lower cost of marginal productivity. The shadow price of either nitrogen fertilizer or other inputs is represented by (3.15). The shadow price of nitrogen fertilizer or other inputs implies how much the farmer’s cost would change by using an additional unit of either nitrogen fertilizer or other inputs. A positive shadow price indicates that the farmers’ cost increases with each additional unit of either nitrogen fertilizer or other inputs used. The value of the shadow price is the maximum amount that a farmer is willing to pay for an additional unit of either nitrogen fertilizer or other inputs. The solution to the first-order conditions yields the conditional input demands which express the cost-minimizing amounts of nitrogen fertilizer and other inputs as functions of exogenous parameters:

\[ X^* (Q_0, w, r, t), Y^* (Q_0, w, r, t) \] (3.16)

The solution to the farmer’s cost minimization problem is represented as:

\[ C^*(Q_0, w, r, t) = (r + t)X^* (Q_0, w, r, t) + wY^* (Q_0, w, r, t) \] (3.17)

(3.17) imply that the least cost possible for the farmer to continue producing the same quantity, \( Q \), which the output prior to the implementation of the tax is \( C^* \).

To analyze the effect of a tax on crop farmers, there is the need to relate Saskatchewan crop farmers’ output to the input quantities used for production. To analyze this effect, the
profit maximization problem or cost minimization problem can be used. However, for simplification, cost minimization problem is used. The farmer’s production function is parameterized using a parametric functional form because it allows to use the data for Saskatchewan crop farmer (Howitt 1995). The specified production indicates the relationship between input quantities and output of Saskatchewan crop farmers. The model adopts the Constant Elasticity of Substitution (CES) production function to allow for different elasticities of substitution between the two inputs, nitrogen fertilizer and other inputs. The CES production function is also used because it requires minimal data (Howitt 1995). Cost minimization presumes the output effect when there is an input price change. The output effect assumes that the farmer maintains the same level of quantity prior to the tax at the least cost possible. After applying the CES functional form to (3.9), the farmer’s output constraint changes to:

\[ Q_0 = A(\beta_1 X^\rho + \beta_2 Y^\rho)^{\frac{1}{\rho}} \]  

(3.18)

The farmer’s new objective function is:

\[ \mathcal{L} = (r + t)X + wY + \lambda( Q_0 - (A(\beta_1 X^\rho + \beta_2 Y^\rho)^{\frac{1}{\rho}})) \]  

(3.19)

The first-order conditions are:

\[ \mathcal{L}_1 = \frac{\partial \mathcal{L}}{\partial X} = r + t - \lambda(\frac{1}{\rho} A(\beta_1 X^\rho + \beta_2 Y^\rho)^{\frac{1}{\rho} - 1} \rho \beta_1 X^{\rho - 1}), \]  

(3.20)

and

\[ \mathcal{L}_2 = \frac{\partial \mathcal{L}}{\partial Y} = w - \lambda(\frac{1}{\rho} A(\beta_1 X^\rho + \beta_2 Y^\rho)^{\frac{1}{\rho} - 1} \rho \beta_2 Y^{\rho - 1}). \]  

(3.21)
The first-order condition (3.20) indicates that the farmer minimizes costs when the marginal product of nitrogen fertilizer is not only equal to the price of nitrogen fertilizer but the tax. The second first-order condition (3.21) indicates that costs is minimized when the marginal product of other inputs is equal to the price. The third condition for the farmer to minimize costs is shown below:

\[ L_3 = \frac{\partial L}{\partial \lambda} = Q_0 - A(\beta_1 X^\rho + \beta_2 Y^\rho)^{1/\rho} \]  
(3.22)

The third condition (3.22) indicates that the farmer spends all his resources on only both inputs when production cost is minimized. The two first order conditions (3.20) and (3.21) are solved for \( Y^* \) to obtain the new conditional input demand for other input. The conditional input demands in (3.16) now take the form (3.23) and (3.24). As shown in (3.23) and (3.24), the conditional input demands are not only a function of quantity, input price but is also now function of the tax on nitrogen fertilizer. The tax on nitrogen fertilizer not only affects the quantity demanded for nitrogen fertilizer but has an effect on the other input:

\[ Y^* = \frac{Q_0 \left( \frac{w}{\beta_2} \right)^{1/\rho^{\rho-1}}}{A \left( \beta_1 \left( \frac{r + t}{\beta_1} \right)^{\rho^{\rho-1}} + \beta_2 \left( \frac{w}{\beta_2} \right)^{\rho^{\rho-1}} \right)^{1/\rho}} \]  
(3.23)

By symmetry the new input demand for nitrogen fertilizer is obtained as shown below in (3.24). This new quantity demanded of nitrogen fertilizer is also function of the tax:

---

18 See Appendix B for the steps in obtaining the new input demands.
\[
X^* = \frac{Q_0 \left( \frac{r + t}{\beta_1} \right)^{\frac{1}{\beta - 1}}}{A \left( \beta_1 \left( \frac{r + t}{\beta_1} \right)^{\frac{\rho}{\beta - 1}} + \beta_2 \left( \frac{w}{\beta_2} \right)^{\frac{\rho}{\beta - 1}} \right)^{\frac{1}{\rho}}} \tag{3.24}
\]

Since the tax imposed on the farmer has an effect on both of the inputs. I need to find out how each input is affected. I differentiate the input demands \( Y^* \) and \( X^* \) to obtain the effect of the tax on each input. The effects of the tax on input quantities demanded is denoted by \( \frac{\partial X^*}{\partial t} \) and \( \frac{\partial Y^*}{\partial t} \) as shown below:

\[
\frac{\partial X^*}{\partial t} = \frac{1}{\rho - 1} \left( \frac{Q_0 \left( \frac{r + t}{\beta_1} \right)^{\frac{2-\rho}{\beta - 1}}}{A \beta_1 \left( \beta_2 \left( \frac{w}{\beta_2} \right)^{\frac{\rho}{\beta - 1}} + \beta_1 \left( \frac{w}{\beta_1} \right)^{\frac{\rho}{\beta - 1}} \right)^{\frac{1}{\rho}}} \right) \tag{3.25}
\]

where \( \frac{\partial X^*}{\partial t} < 0 \), if \( \sigma > 0 \).

The sign of the effect of the tax on nitrogen fertilizer indicates that the quantity of nitrogen fertilizer demanded reduces with the tax.

\[
\frac{\partial Y^*}{\partial t} = -\frac{1}{\rho - 1} \left( \frac{Q_0 \left( \frac{w}{\beta_2} \right)^{\frac{1}{\beta - 1}}}{A \beta_1 \left( \frac{r + t}{\beta_1} \right)^{\frac{\rho}{\beta - 1}} \left( \frac{w}{\beta_1} \right)^{\frac{\rho}{\beta - 1}} \frac{1}{\rho}} \right) \tag{3.26}
\]

where \( \frac{\partial Y^*}{\partial t} > 0 \), if elasticity of substitution, \( \sigma > 0 \).
The sign of the effect of the tax on nitrogen fertilizer indicates that the quantity of other inputs demanded increases with the tax.

3.3 Summary

This chapter provided an overview of the model used to evaluate a GHG reduction policy for Saskatchewan crop farmers. Next is an explanation of the two parts of the model. The first part is the government’s problem followed by a graphical illustration on how the Pigouvian tax set up by the government works and the effect of the tax on crop farmers’ input demands. The second part of the model is the farmer’s problem.
CHAPTER 4 - METHODOLOGY

4.1 Introduction to Chapter

This chapter explains the methods used in carrying out the objectives of this research. The chapter begins with the diagram that depicts the relationship between the agricultural sector, the social planner and the consumer. The rest of the chapter proceeds with a detailed description of how the GHG emissions are estimated, a description of the different soil zones in the study area and an explanation on how the production function is calibrated for Saskatchewan crop farmers.

Figure 4.1. The Agricultural sector, Social planner and Consumer

In Figure 4.1 above, the agricultural industry produces GHG emissions with the goal of minimizing costs subject to the tax. To represent the agricultural sector, I calibrate a production function for a farmer using profit maximization theory. The consumer is exogenous, the goal is to
maximize utility but is negatively affected by the GHGs produced by the agricultural industry. The social planner, which is the federal government, serves as the link between the agricultural sector and consumer sector and applies a tax policy instrument to balance the farmer’s profit with consumer’s utility. The tax set by the social planner has an effect on the agricultural sector. I explore the effect of the tax on farmers using the cost minimization theory.

4.2 Measuring Agricultural GHG Emissions

To calculate the optimal Pigouvian tax for crop production in Saskatchewan, we first need an estimate of GHG emissions from farming practices. This means that emissions would have to be measured consistently on every farm. Agriculture and Agri-Food Canada (2014) devised various means to measure GHG emissions. These methods of measuring GHG emissions includes analyzing carbon changes in the soil, placing measurement chambers in the soil or animal housing, analyzing air tubes placed in the soil, and the use of instrumented towers (Agriculture and Agri-Food Canada 2020b). Apart from the technical difficulties experienced while using these methods of estimating GHG emissions, these methods are capital intensive and time consuming. In addition, farmers have no incentive to estimate emissions on their farm, especially if the measurements would be used to charge them for GHG emissions. To address these measurement problems, farming practices can be connected to GHG emissions through modeling.

Models such as CEEMA and HOLOS developed emission coefficients for various farming activities in Canada. According to the United States Energy Information Administration, an emissions coefficient is a unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (2019). That is, an emission coefficient is the specific amount of GHG emission estimated per unit of an activity or input use. Farming activities such as the cultivation of a crop, manure use, fuel use, fertilizer application, crop residue and manure application each have an emission coefficient (Kulshreshtha et al. 1999).

CEEMA is a widely used model to estimate GHG emissions in various studies across Canada. Dyer et al. (2011) used CEEMA to estimate GHG emissions from feed crops not used in Canadian livestock production. CEEMA has also been used to study GHG emissions from irrigation expansions in Alberta and Saskatchewan (Kulshreshtha and Junkins 2001), implications on GHG emissions due to the expansion of the biofuels industry (Seecharan et al.
estimate the sink potentials of Canadian agricultural soils (Boehm et al. 2004), estimate the impact of policy scenario on GHG emissions and bioenergy production in the Canadian agricultural sector (Liu et al. 2014). CEEMA is comprised of two sub-models, the first sub-model Canadian Regional Agricultural Model (CRAM) for economic planning and the second Greenhouse Gas Emissions Model (GHGEM) for estimating GHG emissions (Kulshreshtha et al. 2002). CRAM is a static, spatial, partial equilibrium mathematical programming model that simulates the production, marketing and transportation of agricultural crops given a land constraint and final product demand (Kulshreshtha et al. 2002). The results from the first sub-model includes: seed quantity, fertilizer quantities, output quantities, input costs and revenue per land area provides a foresight to farmers on what to expect before they embark on production in their prospective farms. The farming activity levels generated from this first sub-model is linked to the second sub-model to develop emission coefficients for farming activities (Kulshreshtha et al. 2002). These emission coefficients are then used to determine the emission levels of a farming activity (Kulshreshtha et al. 2002). For example, to estimate the total amount of direct GHG emission from using a tonne of nitrogen fertilizer on the farm, the emission coefficient per kg is multiplied by the total quantity of fertilizer used, in this case 1000 kg. CEEMA not only covers direct emissions from nitrogen fertilizer but also indirect emissions from leaching and volatilization (Kulshreshtha et al. 2002).

The HOLOS model requires information on farming operations such as type of tillage, land area, irrigation, herbicide, and fertilizer use. Based on these parameters, the model estimates the GHG emissions for a farm. Furthermore, various scenarios of farming practices can be selected to see how they affect the amount of GHG emitted from the farm. HOLOS enable farmers to identify ways to reduce GHG emissions on the farm (Agriculture and Agri-Food Canada 2020a). HOLOS covers both direct and indirect emissions from nitrogen fertilizer (Agriculture and Agri-Food Canada 2020a). An advantage of HOLOS over both IPCC and CEEMA is that HOLOS accounts for carbon sequestered and loss from farm management practices (Agriculture and Agri-Food Canada 2020a).

IPCC developed emission coefficients to estimate direct and indirect emissions from nitrogen fertilizer (2006b). Even though IPCC covers both direct and indirect emissions from nitrogen fertilizer, IPCC encourages the development of region or country-specific emission factors which can account for variability and provide more accurate estimates of emissions (IPCC
Various studies on region specific emissions coefficients have shown deviations from the IPCC’s emission factors (Kulshreshtha et al. 1999; Gabrielle et al. 2006; Leip et al. 2011; Berdanier and Conan 2012). CEEMA was designed specifically for Saskatchewan, which is the study area, HOLOS was designed for Canada while IPCC is for all regions. The difference in the region specifications may be one of the reasons the estimates are significantly different.

4.3 Soil Zones in Saskatchewan

![Saskatchewan Map showing the Different Soil Zones](image)

Source: Saskatchewan Crop Insurance Corporation (2019)

**Figure 4.2. Saskatchewan Map Showing the Different Soil Zones**

The soil type, soil texture, rainfall, previously cultivated crops and organic matter levels are an important consideration in agricultural GHG emissions. Varying soils require different amounts of fertilizer. As shown in Figure 4.2 above, Saskatchewan is characterized by different soil zones: brown, dark brown, black and gray. The brown soil zone is in the southwestern part of Saskatchewan. The brown soil zone covers about 6.3 million hectares, about 69% of the area is cultivated (Agriculture and Agri-Food Canada 2000). The dark brown soil zone lies to the north
and east of the brown soil zone covering about 7.28 million hectares (Agriculture and Agri-Food Canada 2000). The dark brown soil zone is the most cultivated of all the soil zones with about 82% of the area cultivated (Agriculture and Agri-Food Canada 2000). The black soil zone lies east and north of the dark brown soil zone with a size of about 7.52 million hectares (Agriculture and Agri-Food Canada 2000). About 75% of the black soil zone is cultivated. The gray soil zone is at the northern part of the province covering about 4.54 million hectares of land area (Agriculture and Agri-Food Canada 2000). The gray soil zone is the least cultivated of all the soil zones with about 45% cultivated and is sometimes grouped with the black soil zone (Agriculture and Agri-Food Canada 2000).

These soil zones each have varying levels of productivity and require different amount of inputs due to different weather conditions in the soil zones. The black soil zone utilizes the most amount of nitrogen fertilizer followed by the dark brown soil zone and the brown soil zone. For example, according to the 2019 Crop Planning Guide (Government of Saskatchewan 2018, Government of Saskatchewan 2019a), 39 kg of nitrogen fertilizer is recommended for the production of an acre of spring wheat in the brown soil zone, 44 kg in the dark brown zone and 49 kg in the black soil zone (Government of Saskatchewan). Since nitrous oxide emissions depends on the quantity of nitrogen fertilizer used, one would expect the emissions to be highest in the black soil zone and the least in the brown soil zone. Another explanation to why nitrous oxide emissions from nitrogen fertilizer use is highest in the black soil zone is that the wet soil conditions aids the microbial activities that converts synthetic nitrogen fertilizer to atmospheric nitrogen, nitrous oxide is a by-product of this process (nitrification and de-nitrification). As a result, this research considers the input requirements for each of the soil zones in the estimation of the optimal Pigouvian tax for fertilizer use.

4.4 Calibrating the Production Function

I calibrate the agricultural production model for crop farmers in Saskatchewan using the method of Howitt (1995). To solve for the unknown share parameters, specifically, I can take the ratio of the first-order conditions. To calibrate the model, I can use either the cost minimization or profit maximization problem. For ease of use, I make use of profit maximization. Using the profit maximization method requires data of output quantity $Q$, fertilizer quantity $X$, quantities of other inputs $Y$ and costs of fertilizer $r$, costs of other inputs $w$ and elasticity of substitution $\sigma$ to
obtain the unknown share and scale parameters. Also, I calibrate the production function without a tax because this is the crop farmers’ situation prior to government intervention, for which our data is valid. The farmer’s production function is presented below:

\[ Q = A(\beta_1 X^\rho + \beta_2 Y^\rho)^{1/\rho} \]  \hfill (4.1)

The farmers’ profit maximization problem is shown as:

\[
\max \pi = p A(\beta_1 X^\rho + \beta_2 Y^\rho)^{1/\rho} - wY - rX
\]  \hfill (4.2)

Where \( A \) is the scale parameter, \( \beta_1 \) and \( \beta_2 \) are the share parameters and \( \rho = \frac{\sigma - 1}{\sigma} \). The first-order conditions for the farmers’ profit maximization problem are presented below:

\[
\frac{\partial \pi}{\partial X} = \frac{1}{\rho} p \left( A(\beta_1 X^\rho + \beta_2 Y^\rho)^{1/\rho - 1} \beta_1 X^{\rho - 1} \right) - r = 0
\]  \hfill (4.3)

\[
\frac{\partial \pi}{\partial Y} = \frac{1}{\rho} p \left( A(\beta_1 X^\rho + \beta_2 Y^\rho)^{1/\rho - 1} \beta_2 Y^{\rho - 1} \right) - w = 0
\]  \hfill (4.4)

The ratio of the first-order conditions yields:

\[
\frac{\beta_1 X^{\rho - 1}}{\beta_2 Y^{\rho - 1}} = \frac{r}{w}
\]  \hfill (4.5)

This ratio is solved for the unknown share and scaling parameters in the CES production function as a function of the data. The share parameters are solved below:
\[
\beta_2 = \beta_1 \frac{w(X \rho)^{\rho-1}}{r(Y \rho)}
\]  
(4.6)

\[
\beta_1 = 1 - \beta_2
\]  
(4.7)

\[
\beta_1 = \left(1 + \frac{w(X \rho)^{\rho-1}}{r(Y \rho)}\right)^{-1}
\]  
(4.8)

To derive the scale parameter, the production function is solved for \(A\) to yield:

\[
A = \frac{Q}{(\beta_1 X^\rho + \beta_2 Y^\rho)^\rho}\ 
\]  
(4.9)

### 4.5 Summary of Data Used to Calibrate Production Function

The data used in the calibration and calculating the optimal Pigouvian \(t^*\) tax rate is obtained from different sources. I obtain the output and input quantity requirements from the Crop Planning Guide (Government of Saskatchewan 2019a). The crops considered in the research are based on suggested crop rotation schedule in the 2018 Crop planning guide. A summary of the output quantities and fertilizer nitrogen requirements are presented in Table 4.1:
Table 4.1. Output Quantity and Fertilizer Nitrogen Requirements for Saskatchewan Soil Zones

<table>
<thead>
<tr>
<th>Crops</th>
<th>Soil zones</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brown soil zone</td>
<td>Dark brown soil zone</td>
<td>Black soil zone</td>
</tr>
<tr>
<td>Canola</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output quantity</td>
<td>3242</td>
<td>3396</td>
<td>3544</td>
</tr>
<tr>
<td>(kg per hectare)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer quantity</td>
<td>114</td>
<td>120</td>
<td>124</td>
</tr>
<tr>
<td>(kg per hectare)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring wheat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output quantity</td>
<td>3470</td>
<td>4001</td>
<td>4385</td>
</tr>
<tr>
<td>(kg per hectare)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer quantity</td>
<td>95</td>
<td>110</td>
<td>121</td>
</tr>
<tr>
<td>(kg per hectare)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large green lentils</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output quantity</td>
<td>2106</td>
<td>2112</td>
<td>2088</td>
</tr>
<tr>
<td>(kg per hectare)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer quantity</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>(kg per hectare)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPS wheat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output quantity</td>
<td>4230</td>
<td>4412</td>
<td>4923</td>
</tr>
<tr>
<td>(kg per hectare)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer quantity</td>
<td>102</td>
<td>117</td>
<td>61</td>
</tr>
<tr>
<td>(kg per hectare)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed barley</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output quantity</td>
<td>5367</td>
<td>5689</td>
<td>6310</td>
</tr>
<tr>
<td>(kg per hectare)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer quantity</td>
<td>95</td>
<td>101</td>
<td>111</td>
</tr>
<tr>
<td>(kg per hectare)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The values are from 2018 Crop Planning Guide. CPS wheat was not included in the 2019 Crop Planning Guide.

Source: Adapted from the Crop Planning Guide (Government of Saskatchewan 2019a)
The output quantities and fertilizer nitrogen requirements vary across all the soil zones and I consider this variation while estimating the optimal Pigouvian tax rate. As shown in Table 4.1, the brown soil zone has lower yields than the dark brown and the black soil zones with the highest output quantities. The exception is large green lentils with little or no change in the output quantities in all the three soil zones. Based on the weather and climatic conditions in the soil zones, it does not come as a surprise that the fertilizer requirements increase across the soil zones. The brown soil zone requires the least amount of nitrogen fertilizer while the black soil zone requires the greatest amount of nitrogen fertilizer. Apart from the output quantities and input requirements, there are other parameters used in calibrating the production function and calculating the optimal Pigouvian tax rate which are all the same for all the soil zones. These parameters are presented in Table 4.2 below:

**Table 4.2. Parameters for the Calibration of the Production Function**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity of substitution of fertilizer and other inputs</td>
<td>0.7</td>
</tr>
<tr>
<td>Urea ($/tonne)</td>
<td>$570</td>
</tr>
<tr>
<td>Social cost of CO2e ($/tonne)</td>
<td>45</td>
</tr>
<tr>
<td>Consumer Utility</td>
<td>1</td>
</tr>
<tr>
<td>Input Prices</td>
<td>1</td>
</tr>
<tr>
<td>Emission coefficient (kg CO2e/ kg of fertilizer nitrogen)</td>
<td></td>
</tr>
<tr>
<td>• CEEMA</td>
<td>5.96</td>
</tr>
<tr>
<td>• IPCC</td>
<td>7.66</td>
</tr>
<tr>
<td>• HOLOS</td>
<td>8.21</td>
</tr>
</tbody>
</table>

Due to the lack of information on the elasticity of substitution between fertilizer and other inputs Canada, I rely on those used in previous studies in the United States. Yi et al. (2014) set the elasticity of substitution to be 0.21 in their calibration of switch grass production in California. Howitt (1995) uses 0.7 for the elasticity of substitution between inputs for field crop production in California. Hertel et al. (2010) estimates about 1.15 for the elasticity of substitution...
for crop production in Indiana. I make use of 0.7 as the elasticity of substitution used in the calibrating the production function because this value falls between the other two values. I make use of both 0.21 and 1.15 to carry out sensitivity analysis in order to determine how the rate of input substitution between inputs would affect a farmer’s decision when a tax is imposed on nitrogen fertilizer. I make use of farmer’s expenses on both fertilizer and other inputs as the resource allocation. For simplicity, I normalize the price of the two inputs, nitrogen fertilizer and other inputs to 1 (Featherstone and Moss 1994). Also, for simplicity, I assume that consumer utility from crops is linear so that the marginal utility of consumers is constant, and I normalize to 1 (Varian 2014).

I obtain the emission coefficient of fertilizer use from CEEMA, IPCC and HOLOS. The input requirements are reported in lb. per acre from the Crop Planning Guide (2019), however I convert the input requirements to kg per hectare for my estimations and in my results. To estimate the GHG emission coefficient. IPCC (2006) reports the emission coefficient in kg N₂O per tonne of fertilizer nitrogen, I make use of 298 as the CO₂e equivalence of N₂O (Brander and Davis 2012). CEEMA reports the nitrogen content per tonne of nitrogen fertilizer in addition to the IPCC default emission factor, I convert the nitrogen to N₂O using the nitrogen conversion factor of 44/28 (Kulshreshtha et al. 2002). HOLOS reports the emission coefficient in CO₂e per tonne of fertilizer nitrogen.

The social costs of CO₂e used in calculating the optimal Pigouvian tax rate is $45 per tonne CO₂e (Government of Canada 2016). The federal government estimates the social cost of CO₂e for different years, this is the value for the year 2020 (Government of Canada 2016). However, I conduct a sensitivity analysis with the social costs of CO₂e estimates in other years as earlier presented in Table 2.1.
CHAPTER 5 - RESULTS AND DISCUSSION

5.1 Introduction to Chapter

This chapter presents the results of the estimation using the theoretical framework discussed in the previous chapter. The estimated nitrous oxide emissions per kg of synthetic nitrogen fertilizer are the first results to be presented followed by the calculated optimal Pigouvian tax rate per tonne of synthetic nitrogen fertilizer. The next results are the effects of a tax on crop farmers’ input use, emissions and revenue. Lastly, a sensitivity analysis of the rate of input substitution in order to show the relationship between the different rates of input substitution and how crop farmers’ respond to a tax. All the results presented are for the brown soil zones.

5.2 Emissions from Using Nitrogen Fertilizer

I obtain three estimates for nitrous oxide emissions per kg of fertilizer nitrogen using the emission coefficients of HOLOS, CEEMA and IPCC frameworks (Table 5.1). These three estimates are included to allow for accuracy in the estimation of nitrous oxide emissions from nitrogen fertilizer. I estimate the marginal damage per kg of fertilizer nitrogen for each of the three estimates. CEEMA estimates the nitrous oxide emissions from 1 kg of nitrogen fertilizer to be 3.72 kg CO₂e. IPCC estimates nitrous oxide emissions per kg of fertilizer nitrogen to be 4.68 kg CO₂e. Of all the three methods of estimating GHG emissions, HOLOS estimates the highest nitrous oxide emissions with 7.44 kg CO₂e per kg of fertilizer nitrogen. These three estimates of nitrous oxide emissions are all direct emissions from using nitrogen fertilizer. CEEMA estimates the indirect nitrous oxide emissions per kg of fertilizer nitrogen to be 2.24 CO₂e. HOLOS estimates a lower amount of 0.77 kg CO₂e indirect nitrous oxide emissions per kg of fertilizer nitrogen. IPCC estimates the highest indirect nitrous oxide emissions per kg of fertilizer nitrogen to be 2.98 kg CO₂e. The nitrous oxide emissions estimates from CEEMA is the lowest of all three estimates. I include the estimates from CEEMA due to the prevalence of
CEEMA in peer reviewed articles (Dyer et al. 2001; Kulshreshtha and Junkins 2001; Bussler et al. 2001; Seecharan et al. 2002; Boehm et al. 2004; Liu et al. 2014)

Table 5.1. Nitrous Oxide Emissions per kg of Fertilizer Nitrogen in the Brown Soil Zone

<table>
<thead>
<tr>
<th>Model</th>
<th>Direct emissions</th>
<th>Indirect emissions</th>
<th>Total emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEEMA</td>
<td>3.72</td>
<td>2.24</td>
<td>5.96</td>
</tr>
<tr>
<td>IPCC</td>
<td>4.68</td>
<td>2.98</td>
<td>7.66</td>
</tr>
<tr>
<td>HOLOS</td>
<td>7.44</td>
<td>0.77</td>
<td>8.21</td>
</tr>
</tbody>
</table>

5.3 Optimal Pigouvian Tax Rate

I estimate the optimal Pigouvian tax rate based on the amount of CO$_2$e emissions from nitrogen fertilizer. Based on the three estimates of nitrous oxide emissions, I obtain three values for the optimal Pigouvian tax rate. Recall that a tax rate is optimal when it is set equal to the marginal damage from GHG emissions. Since marginal utility of consumer is normalized to 1, the tax rate equals the social cost of CO$_2$e multiplied by the nitrous oxide emissions per tonne of fertilizer nitrogen. At a social cost of $45CAD per tonne CO$_2$e, the Pigouvian tax rate using CEEMA is $268 CAD per tonne of fertilizer nitrogen. With IPCC, I calculate the optimal Pigouvian tax to be $345 CAD per tonne of fertilizer nitrogen. Lastly, the CO$_2$e emissions estimate from HOLOS, I calculate a Pigouvian tax of $370 CAD per tonne of fertilizer nitrogen.

5.4 The Greenhouse Gas Pollution Pricing Act Rate

I estimate the tax rate per tonne of fertilizer nitrogen based on the Greenhouse Gas Pollution Pricing Act amount. The Greenhouse Gas Pollution Pricing Act began with a minimum of $20 CAD per tonne of CO$_2$e and would increase by $10 CAD each year up to $50 CAD in 2022. Based on $10 CAD per tonne of CO$_2$e, the tax rate using CEEMA to estimate nitrous oxide emissions from nitrogen fertilizer use is $60 CAD per tonne of fertilizer nitrogen. With IPCC, the
tax rate is $77 \text{ CAD}$ while HOLOS is $82 \text{ CAD}$ per tonne of fertilizer nitrogen. At $50 \text{ CAD}$ per tonne of CO$_2$e, the tax rate using CEEMA is $298 \text{ CAD}$ per tonne of fertilizer nitrogen. HOLOS is $411 \text{ CAD}$ and IPCC is $383 \text{ CAD}$ per tonne of fertilizer nitrogen.

5.5 **The Effect of a Tax on Nitrogen Fertilizer Use on in the Brown Soil Zone**

The tax estimated in this study demonstrate an effect on nitrogen fertilizer use. This effect of a tax on the brown soil zone is shown in Figure 5.1, Figure 5.2 and Figure 5.3 below:

![Graph showing the effect of a tax on nitrogen fertilizer use in the brown soil zone.](image)

**Figure 5.1. The Effect of a Tax Using Emission Coefficient from HOLOS Framework in the Brown Soil**
Figure 5.2. The Effect of a Tax Using Emission Coefficient from IPCC Framework in the Brown Soil Zone

Figure 5.3. The Effect of a Tax Using Emission Coefficient from CEEMA Framework in the Brown Soil Zone
In Figure 5.1, a Pigouvian tax reduces the amount of nitrogen fertilizer used on the farm. In canola for example, prior to implementation of the tax the farmer uses 114 kg of nitrogen fertilizer per hectare in the brown soil zone. However, after the Pigouvian tax of $268 CAD per tonne of fertilizer nitrogen, the amount of nitrogen fertilizer used per hectare reduces to 87 kg. The reduction in the quantity of nitrogen fertilizer after the Pigouvian tax can also be seen in spring wheat, CPS wheat and feed barley. All of these crops require relatively large amounts of nitrogen fertilizer for cultivation. In other crops like lentils that nitrogen fertilizer is required in relatively smaller quantities for cultivation, there is a reduction in fertilizer use after the Pigouvian tax although the absolute reduction in fertilizer use is small. As shown in Figure 5.2 above using IPCC to estimate nitrous oxide emissions, a Pigouvian tax rate of $345 CAD per tonne of fertilizer nitrogen reduces the amount of fertilizer nitrogen used per hectare from 114 kg to 99 kg in the cultivation of canola. In Figure 5.3, CEEMA is used to estimate nitrous oxide emissions, a Pigouvian tax rate of $370 CAD results in a decrease in fertilizer nitrogen used per hectare from 114 kg to 101 kg.

The Greenhouse Gas Pollution Pricing Act if imposed also reduces the quantity of nitrogen fertilizer used by crop farmers but at a different rate from the optimal Pigouvian tax rate. The effect of the Greenhouse Gas Pollution Pricing Act on crop farmers is presented in Figure 5.4, Figure 5.5 and Figure 5.6 on the next page:
Figure 5.4. The Effect of a Tax Using Emission Coefficient from HOLOS Framework in the Brown Soil Zone

Figure 5.5. The Effect of a Tax Using Emission Coefficient from IPCC Framework in the Brown Soil Zone
Figure 5.6. The Effect of a Tax Using Emission Coefficient from CEEMA Framework in the Brown Soil Zone

As shown in Figure 5.4, Figure 5.5 and Figure 5.6 above, the effect of the Greenhouse Gas Pollution Pricing Act on crop farmer varies depending on the tax rate. In Figure 5.4, the crop farmer was previously using 114kg of nitrogen fertilizer per hectare for canola. After the tax of $82 CAD per tonne of fertilizer nitrogen, the farmer reduces the amount of nitrogen fertilizer used per hectare to 108kg. At a higher tax rate of $411 CAD per tonne of fertilizer nitrogen, the quantity of fertilizer further reduces to 85kg per hectare. In Figure 5.5 using IPCC to estimate nitrous oxide emissions, after the tax rate of $77 CAD per tonne of fertilizer nitrogen, the farmer reduces fertilizer use for canola from 114kg to 98kg per hectare. At $336 CAD per tonne of fertilizer nitrogen, the nitrogen fertilizer used for canola reduces from 114kg to 98kg. The reduction in nitrogen fertilizer due to the tax occurs in other crops like spring wheat, large green lentils, CPS wheat and Barley as shown in Figure 5.4, Figure 5.5 and Figure 5.6. In Figure 5.6 using CEEMA to estimate nitrous oxide emissions, the effect on nitrogen fertilizer use from the tax is quite close in magnitude to IPCC. The effect of a tax on nitrogen fertilizer use on the farm can also be expressed as a percentage as shown in
Table 5.2. The table shows the range of different social costs from $10 to $50 per tonne of CO\textsubscript{2}e. The effect on nitrogen fertilizer use from using each of these social costs of CO\textsubscript{2}e to estimate tax rates is presented. The nitrous oxide emissions from nitrogen fertilizer use is estimated using IPCC, HOLOS and CEEMA frameworks.

<table>
<thead>
<tr>
<th>Tax Rate ($/tonne of CO\textsubscript{2}e)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>45</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPCC (%)</td>
<td>-3</td>
<td>-5</td>
<td>-7</td>
<td>-9</td>
<td>-10</td>
<td>-11</td>
</tr>
<tr>
<td>HOLOS (%)</td>
<td>-5</td>
<td>-9</td>
<td>-14</td>
<td>-16</td>
<td>-17</td>
<td>-22</td>
</tr>
<tr>
<td>CEEMA (%)</td>
<td>-2</td>
<td>-5</td>
<td>-7</td>
<td>-9</td>
<td>-9</td>
<td>-10</td>
</tr>
</tbody>
</table>

In Table 5.2 above, a $10 CAD per tonne of CO\textsubscript{2}e results in a 2%, 3% and 5% decrease in nitrogen fertilizer using CEEMA, IPCC and HOLOS frameworks respectively to estimate nitrous oxide emissions. At $20 CAD per tonne of CO\textsubscript{2}e, nitrogen fertilizer use decreases by 5% using IPCC and CEEMA to estimate nitrous oxide emissions and 9% when HOLOS is used. The decrease in nitrogen fertilizer at $50 CAD per tonne of CO\textsubscript{2}e is about 5 times more than the decrease at a $10 CAD per tonne of CO\textsubscript{2}e. Similarly, in Table 5.2 above, a $45 CAD per tonne of CO\textsubscript{2}e results in 9%, 10% and 17% reduction in nitrogen fertilizer use using CEEMA, IPCC and HOLOS frameworks respectively to estimate nitrous oxide emissions.

5.6 The Effect of a Tax on Farmers’ Profit in the Brown Soil Zone

This study shows that a tax on nitrogen fertilizer has an effect on farmers’ profit. A tax rate set using $10 CAD per tonne of CO\textsubscript{2}e as the social costs results in a reduction in farmers’ profit by 0.7%, 1.1% and 1% for canola, spring wheat and feed barley respectively. At $20 CAD per tonne of CO\textsubscript{2}e, crop farmers’ profit reduces by about 2.2%, 3.9% and 3.6% for canola, spring wheat and feed barley respectively. However, when the price per tonne of CO\textsubscript{2}e increases to $50, the tax reduces crop farmers’ profit by 7%, 12% and 11% for canola, spring wheat and feed barley respectively.
5.7 The Effect of a Tax on Provincial Nitrous Oxide Emissions

This study found an effect of a tax on synthetic nitrogen fertilizer use on the farm also has an effect on nitrous oxide emissions at the farm level and provincial nitrous oxide emissions as shown in Figure 5.7 and Figure 5.8:

![Figure 5.7. The Effect of a $10 per tonne CO2e Tax on Provincial Nitrous Oxide Emissions](image-url)
Figure 5.8. The Effect of a $45 per tonne CO2e Tax on Provincial Nitrous Oxide Emissions

As shown in Figure 5.7 and Figure 5.8 above, a tax if imposed on nitrogen fertilizer use in crop production would reduce nitrous oxide emissions from fertilizer use. Specifically, if the pollution pricing act or the Pigouvian taxes is applied to only nitrogen fertilizer used for three major crops in Saskatchewan, canola, spring wheat and feed barley, it is estimated to reduce total provincial agricultural nitrous oxide emissions by about 5% and 25% respectively.

5.8 Sensitivity Analysis of the Rate of Input Substitution

A sensitivity analysis is carried out to see how the rate of input substitution for N fertilizer influences the effect of a tax on crop farmers in Saskatchewan. The rate of input substitution plays an important role in the response to any policy instrument that changes the price of inputs such as a GHG emissions tax. Using HOLOS estimates of nitrous oxide emissions, the tax rates between $10 to $50 and different rates of input substitution, the effect of the GHG emissions tax vary with each rate of input substitution as shown in Figure 5.9 and Figure 5.10 below:
Figure 5.9. Varying Rates of Input Substitution ($\sigma$) on Fertilizer Use in Canola (Brown Soil Zone)

Figure 5.10. Varying Rates of Input Substitution ($\sigma$) on Fertilizer Use in Spring Wheat (Brown Soil Zone)
As shown in Figure 5.9 and Figure 5.10 above, the higher the rate of input substitution in canola and spring wheat, the more readily the crop farmer reduces the amount of nitrogen fertilizer and substitute nitrogen fertilizer with the other input. This indicates that if farmers have a direct substitute for nitrogen fertilizer in crop production which is indicated by a large rate of input substitution, there is a relatively rapid decline in the amount nitrogen fertilizer use since the crop farmer in response to higher priced nitrogen fertilizer can switch to a less expensive substitute input. For example, if the farmer substitutes nitrogen fertilizer with manure or legumes in the crop rotation which may now be relatively cheaper, the amount of nitrogen fertilizer used on the farm decreases. However, if the crop farmer has no direct substitute for nitrogen fertilizer use indicated by a small rate of input substitution, there is a relatively slow decline in the amount of nitrogen fertilizer use on the farm.

5.9 Sensitivity Analysis with Varying Social Costs of CO\textsubscript{2}E

The federal government has estimated varying social costs of CO\textsubscript{2}e for different years. As a result, the Pigouvian tax is calculated using the social costs of CO\textsubscript{2}e for each year between 2010 - 2050 apart 2020 originally considered. The effect of calculating the optimal Pigouvian tax with the social costs of CO\textsubscript{2}e estimated for different years is shown in Figure 5.11 below:

![Figure 5.11. The Effect of a Nitrogen Tax of Nitrogen Fertilizer Application per Hectare across Several Crops in the Brown Soil Zone](image)

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In Figure 5.11 above, as the social costs of CO₂e used to estimate the optimal Pigouvian tax increases, the amount of nitrogen fertilizer used per acre reduces. This is because the higher the social costs of CO₂e the higher the optimal Pigouvian tax rate.

5.10 Policy Implications

The policy implications from this study indicates the importance of the development of region-specific methods to estimate agricultural nitrous oxide emissions. This is because the use of standard methodologies such as the IPCC emission coefficients may result in biased nitrous oxide estimates (Brown et al. 2001; Flynn et al. 2005). An effective GHG emissions tax internalizes the external costs of GHG emissions which is connected to the amount of GHG estimated (Pearce 2003).

A tax on nitrogen fertilizer apart from reducing nitrous oxide emissions may help farmers to practice more beneficial management practices. For example, due to an increase in input costs from a tax on nitrogen fertilizer, in order for crop farmers to minimize their production costs, crop farmers may reduce the use of nitrogen fertilizer on their farms or may adopt fertilizer application methods that supplies the maximum available nutrients to crops and also with minimal fertilizer run off. Taxes are uncommon in the agricultural industry (Organisation for Economic Co-operation and Development 2003). Warren et al. (2007) states it may be due to the non-point source nature of agricultural emissions and the argument that taxes have a negative impact on farmers’ income. However, fertilizer taxes have been adopted in some parts of Europe and United States (Morris 1994; Pearce and Koundouri 2003). In addition to the tax, the design of an effective GHG reduction policy for the agricultural industry may be more efficient if a reward or compensation is given to farmers who carry out farming practices that reduces the use of nitrogen fertilizer on their farm. This reward or compensation can be from the revenue generated from the fertilizer tax. These payments to farmers are to encourage farmers to adopt farming practices that reduce the use of nitrogen fertilizer on their farms and maintain soil nitrogen stocks. According to Claasen et al. (2001), payments to farmers increases the likelihood that farmers would adopt the beneficial management practice by reducing the net cost of doing so.

This study found that imposing an emissions tax on nitrogen fertilizer would result in a decrease in nitrogen fertilizer use however nitrous oxide emissions may or may not decrease depending on if the farmer adopts farming practices to maintain soil nitrogen stocks. A tax on
nitrogen fertilizer may help Canada achieve the GHG emission reduction goal. The nitrous oxide emissions considered in this research are from the nitrogen fertilizer used in major crops cultivated in Saskatchewan namely wheat, lentils, barley and canola and not all crops. Nitrogen fertilizer used for crop production represents only a small fraction of the agricultural industry. In addition, this estimation of nitrogen fertilizer used for crop production is relatively easier to estimate with the availability of emissions coefficients and the measurability of fertilizer used on the farm. Generally, agricultural emissions are difficult to estimate. Hence, the estimation of nitrous oxide emissions as well as the impact of the emissions tax considered in this research represents a conservative estimate. However, this method of estimating nitrous oxide emissions and the impact of a nitrous oxide emissions tax can be applied to other fractions in the agricultural industry. If the emissions tax is applied to other agricultural practices, it can increase the reduction in provincial agricultural GHG emissions.

5.11 Summary of Chapter

This chapter has discussed the various results of the study that includes the effect of the tax on nitrogen fertilizer use and profit among Saskatchewan crop farmers, the effect on provincial nitrous oxide emissions. This chapter also showed the importance of the rate of input substitution in the effect of a tax on input use. Lastly, this chapter covered how different estimates of the social costs of CO₂e is used to calculate the optimal Pigouvian tax and the effect on various crops as well as the policy implications of a nitrous oxide emissions tax on GHG emissions from nitrogen fertilizer use in crop production.
CHAPTER 6 - SUMMARY AND CONCLUSION

6.1 Introduction to Chapter

This chapter discusses the contribution of this research to previous studies and some of the limitations faced while carrying out this study. Lastly, suggestions are made for future research.

6.2 Contribution of Research

Various research has developed emission coefficients for observable farming practices such as the use of synthetic nitrogen fertilizer use. This research contributes to previous studies by using the emission coefficients to measure nitrous oxide emissions from using synthetic nitrogen fertilizer among crop farmers in Saskatchewan. By estimating nitrous oxide emissions using IPCC, HOLOS and CEEMA, this research shows the difference in the nitrous oxide emission estimates from nitrogen fertilizer application among all three frameworks. In addition, this research is the first to calculate an optimal Pigouvian tax rate per tonne of fertilizer nitrogen and estimate how a nitrous oxide emissions tax would affect crop farmers’ input use and profits as well as the effectiveness in reducing provincial nitrous oxide emissions.

6.3 Limitations

We use the cost minimization framework in this study, which necessarily holds output fixed. However, the major limitation of this study is that the theoretical model used does not allow for changes in output, changes in crop mix and larger changes in land use. While this is a restrictive assumption, the assumption is because the level of emissions tax considered is likely not large enough to induce such changes. Subsequent work analyzing larger emissions tax values would have to consider the possibility of changes to the output mix. As a result, this analysis should be interpreted carefully for policy.
Another limitation of this analysis is that this model does not account for carbon sequestration. Carbon sequestration not only depends on land use and management but also biophysical factors (Hijbeek et al. 2019). Studies show that higher levels of fertilizer nitrogen increase soil carbon stocks by increasing crop residue due to more biomass from higher crop yields (Ju et al. 2009, Kirkby et al. 2016), increasing crop yields that capture carbon through photosynthesis (Baldock et al. 2012). Other studies show that there may be an increase in nitrous oxide emissions from increased use of fertilizer nitrogen as all nutrients released from decomposing soil residue may not necessarily be taken up by crops (Hijbeek et al. 2019). The carbon sequestered may not offset the nitrous oxide emissions since nitrous oxide is about 300 times more potent greenhouse gas than carbon dioxide (Del Grosso et al. 2008), hence increased fertilizer nitrogen may increase total GHG emissions. In addition, more studies show that nitrogen fertilizer may be of little benefit to soil carbon sequestration (Russell et al. 2005, Follett et al. 2005, Machado et al. 2006, Sainju et al. 2006).

Physical estimation of nitrous oxide emissions will provide an accurate measuring of nitrous oxide emissions from synthetic nitrogen fertilizer used on the farm due to the varying biophysical characteristics of farms. However, using instruments to estimate nitrous oxide emissions on the farm is an expensive process and the farmer may require technical know-how of the instruments. Hence the use of emissions coefficients that have been developed for farming practices. Currently, these emissions coefficients are only available for observable farming practices such as synthetic nitrogen fertilizer. There are other sources of nitrous oxide emissions on the farm such as manure use and management, crop residue burning. These other sources of nitrous oxide emissions are not easily observable; hence it was difficult estimating the nitrous oxide emissions from these other sources. As a result, these other sources of nitrous oxide emissions are omitted.

Lastly, The Greenhouse Gas Pollution Pricing Act is a relatively new policy and the federal government continues to make adjustments to the policy. Future adjustments or changes made to the Greenhouse Gas Pollution Pricing Act may affect the validity of the results from this research.
6.4 Future Research

There are varying sources of nitrous oxide emissions on the farm such as manure use and management. There is the need for research into estimating GHG emissions from these other sources of nitrous oxide and other GHG emissions on the farm. An example is to calculate emission coefficients for these farming practices or develop cheaper, simpler but equally effective measuring instruments. The need to estimate emissions from other sources of nitrous oxide as well as other GHGs.

In order for the federal government to use an emissions tax as a measure to reduce agricultural emissions, tax rates need to be estimated for various farm practices such as manure use and crop residue burning.

6.5 Summary

Using an emissions tax as an instrument to reduce nitrous oxide emissions from annual crop production imposes important tradeoff costs. This is because a tax levied on synthetic nitrogen fertilizer has the ability to effectively reduce the use of synthetic nitrogen fertilizer and also provincial GHG emissions. At the same time, the imposition of an emissions tax on synthetic nitrogen fertilizer results in a significant reduction in crop farmers’ profits. A policy suggestion to using a tax is for crop farmers who are currently carrying out beneficial farm practices that reduce GHG emissions on their individual farms to be compensated through subsidies or other forms of payments.

As demonstrated in this study, a tax imposed on nitrogen fertilizer use in crop production can significantly reduce GHG emissions. However, implementing an emissions tax in Saskatchewan is difficult due to the strong political power of farmers and farmers may need to be actively involved in order to estimate agricultural emissions. In order words, the success of an emissions tax applied to the agricultural industry may depend on the support from farmers.
REFERENCES


Appendix A: Deriving the Optimal Tax Rates

By invoking the envelope theorem in (3.3) yields:

\[ \frac{\partial R}{\partial t^*} = -X^* \]

Put \( \frac{\partial R}{\partial t^*} = -X^* \) in equation \( \frac{\partial W}{\partial t^*} = U'(G) \left( \frac{\partial R}{\partial t^*} + X^* + t^* \frac{\partial X^*}{\partial t^*} \right) - \delta \left( e \frac{\partial X^*}{\partial t^*} \right) = 0 \) and this yields:

\[ \frac{\partial W}{\partial t^*} = U'(G) \left( -X^* + X^* + t^* \frac{\partial X^*}{\partial t^*} \right) - \delta \left( e \frac{\partial X^*}{\partial t^*} \right) = 0 \]

Move \( \delta \left( e \frac{\partial X^*}{\partial t^*} \right) \) to the right-hand side:

\[ U'(G) \left( t^* \frac{\partial X^*}{\partial t^*} \right) = \delta \left( e \frac{\partial X^*}{\partial t^*} \right) \]

Divide both sides by \( \frac{\partial X^*}{\partial t^*} \) yields:

\[ U'(G)t^* = \delta e \]
Solve for $t^*$:

$$t^* = \frac{\delta e}{U'(G)}$$
Appendix B: The Conditional Input Demands with a Tax

From (3.20), I solve $L_1$ for $r + t$ and, divide $r + t$ by $w$ to obtain:

$$r + t = \frac{1}{\rho} A(\beta_1 X^\rho + \beta_2 Y^\rho)^{1-\rho} \rho_1 X^{\rho-1}$$

From (3.21), I solve $L_2$ for $w$ to obtain:

$$w = \frac{1}{\rho} A(\beta_1 X^\rho + \beta_2 Y^\rho)^{1-\rho} \rho_1 Y^{\rho-1}$$

Divide $r + t$ by $w$ to obtain:

$$\frac{r + t}{w} = \frac{\rho_1 X^{\rho-1}}{\rho_2 Y^{\rho-1}}$$

Solve the ratio for $X$:

$$X = \left( \frac{r + t}{\beta_1} \right)^{1-\rho} \left( \frac{w}{\beta_2} \right)^{-1-\rho} Y$$

Put $X$ into $L_3 = Q_0 - A(\beta_1 X^\rho + \beta_2 Y^\rho)^{1}$ to obtain:

$$L_3 = Q_0 = A\{ \beta_1 \left( \frac{r + t}{\beta_1} \right)^{\rho} \left( \frac{w}{\beta_2} \right)^{-\rho} Y^\rho + \beta_2 Y^\rho \}^{1}$$
Since $Y^\rho$ is common to both sides, collect $Y^\rho$:

$$L_3 = Q_0 = A\{Y^\rho\left(\frac{r + t}{\beta_1}\right)^{\frac{\rho}{\rho - 1}}\left(\frac{w}{\beta_2}\right)^{\frac{\rho}{\rho - 1}} + \beta_2\}\}^{\frac{1}{\rho}}$$

Solve for $Y^\rho$:

$$L_3 = Q_0 = A\{Y^\rho\left(\frac{\beta_2 r + t}{\beta_1 w}\right)^{\frac{\rho}{\rho - 1}} + \beta_2\}\}^{\frac{1}{\rho}}$$

$$Y^\rho = \frac{Q_0}{A\left\{\left(\frac{r + t}{\beta_1}\right)^{\frac{\rho}{\rho - 1}} + \beta_2 \left(\frac{w}{\beta_2}\right)^{\frac{\rho}{\rho - 1}}\right\}^{\frac{1}{\rho}}}$$

To solve for $Y^*$, raise both sides by $\frac{1}{\rho}$:

$$Y^* = \left(\frac{Q_0}{A\left\{\left(\frac{r + t}{\beta_1}\right)^{\frac{\rho}{\rho - 1}} + \beta_2 \left(\frac{w}{\beta_2}\right)^{\frac{\rho}{\rho - 1}}\right\}^{\frac{1}{\rho}}}\right)^{\frac{1}{\rho}}$$

Similar steps apply in order to obtain $X^*$. 