What is the Optimal Rate and N_2O Mitigation Policy for Nitrogen Application in Saskatchewan Canola?

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By

Michelle Ross

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Dean
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ABSTRACT

This thesis examines privately and socially optimal nitrogen (N) fertilizer rates for Canola production in Saskatchewan. In 2018 nitrous oxide (N_2O) emissions from agricultural soils accounted for approximately 42% (in CO_2eq) of all Canadian agricultural greenhouse gas emissions. In 2020 the Government of Canada set a national target of reducing absolute levels of GHG emissions from fertilizer application by 30% from 2020 levels by the year 2030. Canola is the largest N using crop in Canada and therefore optimizing N fertilizer use in this crop is of great importance. A canola production function is estimated using a large (n = 47,059) producer-reported data set from Saskatchewan Crop Insurance Corporation on field-level canola management over the years 2011-2019 and a wide variety of spatial and climatic conditions. The estimated implied canola N response curve was combined with price information and previous estimates for direct N_2O emissions to estimate the marginal abatement cost curves and compare the observed applied N fertilizer rates to the estimated privately optimal rates and socially optimal rates. The results of this study support the previous findings of a nearly flat pay-off function for N fertilizer in crop production. On average, Saskatchewan canola producers do not appear to be overapplying nitrogen relative to the estimated privately optimal N rate. Regulation to reduce nitrogen fertilizer application rates by 30% from the privately optimal rate were found to result in net social welfare losses for canola cropping systems in Saskatchewan. When applying a N_2O tax using the highest carbon price in the Canadian governments' schedule of \$170 t^{-1} CO_2eq for 2030, N rates are estimated to be reduced from the privately optimal rate by only 12.3% – 14.6% in the black soil zone and 6.12% – 6.92% in the brown soil zone. Given the heterogeneity in emissions factors across ecoregions and nitrogen management practices, focusing on the 4R's of Nutrient Stewardship, agronomic research, and extension to improve N management and optimize fertilizer use are better opportunities to reduce emissions as opposed to a uniform mandatory reduction in N rates.

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LIST OF ABBREVIATIONS

AB	Alberta
AME	average marginal effect
AP	average precipitation
AW	Archerwill
B.C.	British Columbia
CGE	computable general equilibrium
CI	crop insurance
CL	Clearfield
CO_2	carbon dioxide
CO_2 eq	carbon dioxide equivalent
CPI	consumer price index
CR	cost ratio
DWL	dead weight loss
EF	emissions
EONR	economically optimal nitrogen application rate
ESN	environmentally smart nitrogen
FE	fixed effects
GDD	growing degree days
GHG	greenhouse gas
GS	growing season
HRSW,	hard red spring wheat
HWS,	hard spring wheat
ID	identification
IQR	Interquartile range
IH	Indian Head
IPCC	Intergovernmental Panel on Climate Change
K	potassium
LL	Liberty Link
LLD	land location
MB	Manitoba
MC_N	marginal cost of nitrogen
MEM	marginal effects at the means
N	nitrogen
N_2O	nitrous oxide
NO_3	nitrate
NR	net revenue
ODD	overheat degree days

OLS	ordinary least squares
P	phosphorous
P_N	price of nitrogen
PP	Porcupine Plaine
RR	Roundup Ready
RZ	risk zone
S	sulphur
SAMA	Saskatchewan Assessment Management Agency
SC	Swift Current
SCIC	Saskatchewan Crop Insurance Corporation
SK	Saskatchewan
t	Metric tonne
SMP	Saskatchewan Management Plus
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
VIP	Variable importance in projection
VMP_N	value of marginal product of nitrogen
WFSP	water-filled pore space

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CHAPTER 1 INTRODUCTION

1.1 Background

In 2018 nitrous oxide (N_2O) emissions from agricultural soils accounted for approximately 42% (in CO_2eq) of all Canadian agricultural greenhouse gas emissions (Environment and Climate Change Canada, 2021). The primary driver of N_2O emissions in agriculture is nitrogen fertilizer use which has increased by 71%, over the years 2005-2019 and led to record Canadian crop production but also a 54% increase in N_2O emissions over the same time period (Environment and Climate Change Canada, 2021; Government of Canada, 2022). In December 2020, the Canadian federal government set a national target to reduce absolute levels of GHG emissions from fertilizer application by 30% from 2020 levels by the year 2030 (Government of Canada, 2022). The federal target to reduce GHG emissions from fertilizer application poses a challenge in the production of nitrogen intensive crops, such as canola which is one of Canada's leading agricultural exports that added $29.9 billion to the national economy in 2019 (Canola Council of Canada, 2020). There is currently a growing biofuel market for canola in response to clean fuel standard policies which has led to the announcement of approximately $2 billion of expanded Canadian canola processing in 2021 (Canola Council of Canada, 2022). However, the high nitrogen application rates required to grow canola to meet increasing global demand are in tension with the Canadian federal government's ambitious GHG emission targets regarding fertilizer use (Government of Canada, 2022). Canola is the largest N using crop in Canada and therefore optimizing nitrogen fertilizer application is crucial, not only to increase canola yields (Cutforth, et al., 2009) and improve nitrogen use efficiency (Blackshaw, et al., 2010), but to reduce the carbon footprint of canola (Gan, et al., 2011).

1.2 Motivation and Objectives

The optimization of nitrogen fertilizer is important from both a producer profit and environmental perspective and the optimal nitrogen rates in crop production have been extensively studied using experimental field data (Rajsic & Weersink, 2008; Rajsic, Weersink, & Gandorfer, 2009; Meyer-Aurich et al., 2010). Frequently, flat pay-off functions are estimated for crop production inputs, where even large deviations from the economically optimal level of input make little difference to the payoff which is a potential reason why some producers overapply nitrogen (Pannell 2006, 2017). Previous studies in corn production in Ontario, Canada have shown that producers are applying nitrogen at rates above those that are privately optimal. Although the economic costs of overapplying may be small due to the flat-payoff function, reducing nitrogen rates from historical regional rates in corn production in Ontario has been found to increase profit over time on average while simultaneously decreasing N_2O emissions, decrease volatilization and leaching (De Laporte, et al., 2021). From a policy perspective, this suggests that reducing nitrogen application through policies such as a nitrogen cap or adding a tax to nitrogen bought could result in both environmental and farm profit advantages (De Laporte, et al., 2021).

The potential environmental and economic benefits of reducing N application has been found in the context of Ontario corn production (De Laporte, et al., 2021). However, further research is needed on the implications of reduced N use in the context of canola, which is a high N user and the leading field crop in Saskatchewan. There is also a lack of studies using farm-level data to estimate the canola nitrogen response curve and economic optimal N application rate. Using a large, producer reported field-level canola management data set from Saskatchewan Crop Insurance Corporation, this thesis will fill this gap in the literature by using farm-level N application rates over a wide variety of spatial and climatic conditions to estimate the implied canola nitrogen response curve and assess whether reducing N application rates in the context of canola production in Saskatchewan is a feasible N_2O mitigation strategy. The specific objectives of this thesis are to:

1. Estimate the privately optimal rate of N application for Canola in Saskatchewan using a large, producer reported field-scale data set;
2. Estimate the marginal abatement cost for direct N_2O emissions from N fertilizer application in Saskatchewan;
3. Compare an optimal Pigouvian tax on N fertilizer use to a regulated 30% reduction in N fertilizer use for Saskatchewan canola.

1.3 Overview of Methods & Findings

Using the producer reported canola management data set from Saskatchewan Crop Insurance Corporation, the Saskatchewan canola production function was estimated. The canola production model is a function of agro-ecological, variable inputs and management factors and was estimated using an OLS regression with fixed effects for soil class, risk zone and producer by year. The estimated canola nitrogen response curve was combined with price information and previous estimates for direct nitrous oxide emissions to estimate the marginal abatement cost curves and compare the observed applied N fertilizer rates to the estimated privately optimal and socially optimal rates. The results of this study support the previous findings of a flat pay-off function for nitrogen fertilizer in crop production (Pannell, 2017). The results suggest that on average Saskatchewan canola producers do not appear to be overapplying nitrogen relative to the estimated privately optimal N rate. When applying a N_2O tax using the highest carbon price in the Canadian governments' schedule of \$170 t^{-1} CO_2eq for 2030, nitrogen rates are estimated to be reduced from the privately optimal rate by only 12.3 – 14.6% in the black soil zone and 6.12 – 6.92% in the brown soil zone. At a 40 kg ha^{-1} reduction in nitrogen fertilizer from the economic optimum, the GHG abatement cost is estimated to be \$381 t^{-1} CO_2eq for the brown soil zone and \$190 t^{-1} CO_2eq for the black soil zone while the abatement costs are even greater in the case that producers are already underapplying nitrogen relative to the privately optimal N. Regulation to reduce nitrogen fertilizer application rates by 30% from the privately optimal rate were found to result in net social welfare losses for canola cropping systems in Saskatchewan. Given the heterogeneity in emissions factors across ecoregions and nitrogen management practices, focusing on the 4R's of Nutrient Stewardship, agronomic research, and extension to improve nitrogen management and optimize fertilizer use are better opportunities to reduce emissions as opposed to a uniform mandatory reduction in N rates.

1.4 Organization of the Study

This rest of this thesis is organized as follows: Chapter 2 is a review of the existing literature. Chapter 3 details the conceptual framework and chosen methodology. Chapter 4 describes the data used in analysis while Chapter 5 discusses the estimation process followed by the regression results and the estimates for the privately optimal nitrogen use. Chapter 6 presents the environmental policy scenario results including the marginal N_2O abatement cost from reduced nitrogen fertilizer application and the effects of a socially optimal N_2O tax on direct emissions. Finally, this thesis is concluded in Chapter 7 with a summary of results and implications.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The following literature review provides theory of environmental policy and factors of canola production in Saskatchewan. The literature on environmental policy is discussed to understand the theory of carbon pricing, carbon leakage and the current carbon pricing system in Canada. A review of previous findings on carbon tax policies within the North American agriculture industry is provided. Studies that have researched the GHG mitigation cost of nitrogen fertilizer, policies that reduce nitrogen application and tax N_2O emissions were reviewed. The literature on canola production in Saskatchewan is examined to understand the wide range of management and environmental factors that influence yields with an in-depth review of the nitrogen response function and economic optimum as this is a major focus of this thesis.

2.1.1 Emissions from Nitrogen Fertilizer Application

Climate change is arguably the greatest issue of our time. Canada has committed to reducing national emissions by 40-45% from 2005 levels by 2030 under the Paris climate accord in the face of this global crisis. Nitrous oxide (N_2O) emissions from agricultural soils accounted for approximately 3% of anthropogenic emissions in Canada in 2017 (Environment and Climate Change Canada, 2018). Nitrous oxide is a much more potent greenhouse gas than carbon dioxide, with the effect of 1 pound of nitrous oxide on warming the atmosphere being nearly 300 times that of 1 pound of carbon dioxide. Nitrogen fertilizer consumption has increased by 150% in Western Canada from 1981 to 2011, which is much larger than the Eastern Canada trend of increased consumption over the same time period which is estimated to be 22%. The increase in nitrogen fertilizer use has contributed to record crop production in Canada but has also resulted in increased N_2O emissions. Since 1990, N_2O emissions from agricultural soils have increased by 50% and in 2016 accounted for 75% of the national N_2O emissions in Canada (Environment and Climate Change Canada, 2018). The net GHG emissions have slightly decreased from 1981 levels due to adoption of reduced tillage and summer fallow (Government of Canada., 2020). However, the use of synthetic fertilizers accounts for 17.5% (12.75 Mt) of Canada’s agriculture GHG emissions (Environment and Climate Change Canada, 2018). The Canadian federal government has a national target of reducing absolute levels of GHG emissions from fertilizer application by 30% from 2020 levels by the year 2030 (Government of Canada, 2022). Reducing emissions from nitrogen fertilizer, while meeting the food production demands of a growing population poses a great challenge.

To understand potential solutions to this challenge, there first must be an understanding of the factors that affect N_2O emissions from nitrogen fertilizer application. The IPCC's approach to estimate N_2O from agricultural soils identifies two main sources: soil mineral nitrogen, applied fertilizer-N and crop residue nitrogen (IPCC, 2013). Use of nitrogen fertilizer has been identified as a primary driver of the increasing concentration of in N_2O in the atmosphere (Forster, et al., 2007). N_2O is produced in agricultural soils through the processes of denitrification and nitrification. These processes are mainly controlled by soil moisture, temperature, labile organic C, oxygen availability, nitrate and ammonium concentrations and pH (Bouwman, 1990; Bouwman, 1996; Butterbach-Bahl, Baggs, Dannenmann, et al., 2013; Farquharson & Baldock, 2008). There have been numerous previous studies that aim to empirically estimate the N_2O emissions from agricultural soils. Nitrous oxide emissions in croplands have been found to be affected by soil, climate, and management factors. Soil factors include texture, drainage, and bulk density. Climate factors include temperature and rainfall. Management factors include fertilizer applied, crop type and tillage (Kaiser, et al., 1996; Jungkuns, Freibauer, Neufeldt, et al., 2006; Flechard, et al., 2007). Acknowledging the importance of the management factors that affect N_2O emissions, Fertilizer Canada provides the 4R's of Nutrient Stewardship approach. The 4R's of Nutrient Stewardship are the right source at the right rate, right time and right place which are best management practices to improve nutrient management and reduce associated emissions. The environmental impacts of N_2O emissions from nitrogen fertilizer are particularly of concern in the production of nitrogen intensive crops, such as canola.

2.1.2 Canola: High Nitrogen Use Crop with Growing Demand

Canola is a high nitrogen use crop which is used for food, food, and fuel. Canola is a very economically important for Canada, as the canola industry added $29.9 billion to the national economy in 2019 and is one of Canada's leading agricultural exports (Canola Council of Canada, 2020). Canada is the largest producer of canola globally with the province of Saskatchewan alone accounting for 54% of Canadian canola acres in 2016 (Statisitics Canada, 2018). There has been a large increase in canola production over the past 25 years, which in part is due to growing demand for edible oil, seed, meal, and biodiesel products (Harker, et al., 2011). There is currently a growing biofuel market for canola in response to clean fuel standard policies that have been implemented by several countries. In Canada, the CFR (Code of Federal Regulations) requires that transportation in fuels have an incremental carbon intensity reduction reaching 15% by the year 2030 (Canadian Canola Growers Association, 2022).The strong demand for canola has resulted in approximately $2 billion of expanded canola processing announcements since 2021 (Canola Council of Canada, 2022). In the spring of 2021, Richardson International, Cargill, Viterra, and Ceres Global Ag each announced new development plans to expand canola crushing in Saskatchewan, which totaled 5.7 million metric tonnes in additional crushing capacity (Leader Post, 2021; Richardson International Ltd., 2021). Canola is seeing growing demand due to its use as a biodiesel in response to clean fuel standard policy around the world. However, the high nitrogen application rates required to grow canola on the Saskatchewan prairies result in emissions that are in tension with the Canadian federal government's own target of reducing absolute levels of GHG emissions from fertilizer application by 30% from 2020 levels by the year 2030 (Government of Canada, 2022). Therefore optimizing nitrogen fertilizer application is crucial, not only to increase canola yields (Cutforth, et al., 2009) and improve nitrogen use efficiency (Blackshaw, et al., 2010), but to reduce the carbon footprint of canola (Gan, et al., 2011).

2.1.3 Optimizing Nitrogen Fertilizer Use

The optimization of nitrogen fertilizer is important from both a producer profit and environmental perspective and the optimal nitrogen rates in crop production have been extensively studied (Rajsic & Weersink, 2008; Rajsic, Weersink & Gandorfer, 2009). However, the models used to estimate the economically optimal levels of production inputs at the field level often result in wide profit plateaus. Frequently, flat pay-off functions are estimated for nitrogen fertilizer where even large deviations from optimal levels make little difference to the payoff (Pannell, 2006). The profit plateau occurs due to the usual shape of the production function which is generally smooth and because marginal profitability is necessarily close to zero in the region of the optimum (Pannell, 2006). The flat profit function of nitrogen application may be a rationale as to why some producers over apply nitrogen as the use of excessive rates sacrifices a relatively small amount of profit (Pannell, 2017). Another reason why producers may overapply nitrogen is due to uncertainty as previous works have found that overapplying nitrogen may be due to a producers preference to maximize good years by applying more than enough nitrogen to limit the risk of turning good years into less good years (Rajsic, Weersink, & Gandorfer, 2009). A study by Rajsic & Weersink (2008) in corn in Ontario, Canada found that overapplying N could also be related to farmers making fertilizer decisions ex ante before growing season information is known which look worse compared to the estimation of optimal rates that are conducted ex post when growing season information is known (Rajsic & Weersink, 2008). Although the economic costs of overapplying may be small due to the flat-payoff function, reducing nitrogen rates from historical regional rates in corn production in Ontario has been found to increase farm profit, decrease N_2O emissions, decrease volatilization and leaching (De Laporte, et al., 2021). De Laporte et al., (2021) finds that the 4R (Right Source, Right Rate, Right Time, and Right Placement) N guidelines for corn can increase profitability by 40% while decreasing the N application rate by 21% reduction. These findings suggest the potential benefits of environmental policies that reduce nitrogen application such as a nitrogen cap in an area or adding a tax to nitrogen bought (De Laporte, et al., 2021). The next section will review environmental policy and provide an overview of studies regarding nitrogen fertilizer use taxation.

2.2 Environmental Policy

Environmental policy is increasingly important in the face of climate change as regulators need policy tools to reduce GHG emissions. The IPCC (2018) advocates for policy incentives to reduce GHG emissions in order to emerge as a net-zero carbon energy-economy near 2050 (IPCC, 2018). The IPCC states that environmental policy needs to be stringent and integrated in order to achieve this with recommended potential methods including explicit carbon pricing, direct regulation, and public investment in innovation (IPCC, 2018). The IPCC conclude from emerging literature that carbon pricing mechanisms, such as a carbon tax, can potentially achieve cost-effective emission reductions (IPCC, 2018). There is extensive literature dedicated to investigating which environmental policies are effective in reducing GHG emissions to mitigate climate change. Economic literature indicates that a direct price for emissions, through a tax or a tradable permit, is the most efficient incentive to reduce GHG emissions (Shahzad, 2020; Baranzini, 2017; Fischer & Newell, 2008). Fischer and Newell (2008) assess the cost-effectiveness of different environmental policies for reducing carbon dioxide emissions and promoting innovation. Their results support direct pricing of emissions as the most efficient single policy for reducing GHG emissions. However, results also indicate that the most optimal, cost-effective policy to reduce GHG emissions is one that includes emission pricing and technology policy (Fischer & Newell, 2008; Baranzini, 2017). Carbon pricing and technology policies are largely complementary, and both may be needed for effective carbon policy. Carbon pricing internalizes the global warming externality while innovation subsidies are needed to internalize the positive, knowledge externalities of innovation (Baranzini, 2017). In recent decades, the use of environmental taxes has increased in popularity in developed countries, especially among OCED and European countries to combat climate change (Shahzad, 2020). Canada imposed a carbon tax in 2018 in an attempt to reduce national GHG emissions which will be further discussed in section 2.2.2.

2.2.1 Carbon Leakage

A concern with a unilateral carbon pricing policy is the potential for emissions leakage between countries. Emissions leakage occurs when emissions reductions in countries results in increased emissions in other countries (Baranzini, 2017). In the case of emissions leakage, a theory often discussed is the pollution haven hypothesis. This theory proposes that when environmental regulations are implemented industries with high emissions will relocate to ‘pollution havens’ or countries with less stringent environmental regulations (Copeland & Taylor, 2004). Therefore, in assessing the net GHG impact of environmental policies it is important to consider potential leakage, including land-use changes (Dumortier & Elobeid, 2021). An example of a policy that aimed to reduce emissions in the face of climate change but has been challenged due to the potential unintended consequences is that of clean fuel standards and the expansion of biofuel production. Biofuel production has been seen as a potential solution to the GHG emissions from fossil fuels. However, studies have found that the indirect land-use changes as a result of biofuel expansion can in fact result in increased carbon emissions. As biofuel expansion results in displacement of existing production of other crops, land with high carbon sequestration may be converted turned into cropland (Searchinger, et al., 2008). Therefore, environmental policies must be studied carefully with consideration given to carbon leakage and unintended consequences.

Economists recognize GHG emissions from nitrogen fertilizer applications as external costs as producers who apply nitrogen do not bear these costs. These external costs can result in market failure where the decisions by unregulated producers in a free market lead to outcomes that are not in the best interests of society which therefore justifies some form of government intervention (Pannell, 2017). The implementation of a carbon tax on nitrogen fertilizer is intended to correct the negative externality of pollution. However, there are concerns regarding the global net GHG emission effect of unilateral carbon pricing policies. Under a unilateral carbon tax, differences in polices across countries can lead to carbon leakage. As a result of a carbon price policy in one country, national emissions may increase in a country without a carbon price policy (Elliott, et al., 2010; Elliot & Fullerton, 2014). The increase in emissions may offset some of the reductions achieved by the carbon pricing policy and in the worst scenario increase global emissions (Dumortier, et al., 2012; Arroyo-Curra´s, et al., 2015). This theory has been studies in the case of a price on carbon. The OECD (2019) utilized a Modular Applied General Equilibrium Tool (MAGNET) model to varying global carbon tax situations. The carbon price within the simulations ranged from \$40 – \$60 per tonne of CO_2 equivalent resulting in a 35% reduction in emissions by 2050. However, a carbon tax imposed on OECD member countries, while reducing emissions by 29% in OECD countries, only reduced global emissions by 2%. These results are attributed to significant emissions leakage and trade shifts to heavier emitting production systems (OECD, 2019). The effect of a carbon tax policy is a function of the interactions between the production cost, land-use decisions, prices and international trade (Dumortier & Elobeid, 2021).In order to mitigate carbon leakage, a global carbon price would need to be developed to mitigate the incentives for countries to free ride. However, the global political economy and international coordination of climate policy are huge challenges to developing a global carbon price (Baranzini, 2017). In the absence of a global carbon price, a unilateral carbon pricing policy needs to be studied carefully to examine the global GHG impact due to carbon leakage (OECD, 2019) .

2.2.2 Canadian Carbon Pricing

In 2018, Canada enacted the Greenhouse Gas Pollution Pricing Act. This act set a pollution price by placing a price on fossil fuels like natural gas and gasoline known as the fuel charge as well as a performance-based system for industries known as the Output-based Pricing system. The output-based pricing system for industry large-emitters was scheduled at $30 per tonne of carbon equivalent emissions for 2021. In December of 2020, the Canadian federal government announced a plan to increase the tax to $170 per tonne of CO_2 equivalent emissions by 2030 (Government of Canada, 2022; The Natonal Post, 2020). There is not currently a direct carbon tax on nitrogen fertilizer application in Canada. Nitrogen fertilizer contributes to GHG emissions through the energy-intensive manufacturing process and the release of nitrous oxide into the atmosphere from agricultural soils following application. Under the current federal carbon pricing policy, Canadian nitrogen fertilizer manufacturers incur the carbon tax through the Output-Based Pricing System (Fertilizer Canada, 2022). Producers may incur the tax as the additional costs of fertilizer manufacturing are passed on from the manufacturers to producers. It is important to note that the world price of nitrogen fertilizer has a large impact on Canadian fertilizer prices, hence this tax may be borne largely by Canadian nitrogen producers. While there is not currently a specific tax on nitrogen fertilizer use in Canada, potential environmental policies regarding nitrogen applications are worthy of research due to the substantial associated emissions and ambitious national emission targets. The following will overview previous research on carbon tax policies in the context of North American agriculture.

2.2.3 Carbon Tax in North American Agriculture

The effects of a carbon tax on the agricultural industry has been the focus of several economic studies. Studies have investigated the impact of carbon tax policies on the agricultural industry using both econometric modelling (Rivers & Schaufele, 2013; Olale, Yiridoe, Ochuodho, et al., 2019) and equilibrium modelling (Dumortier & Elobeid, 2021; Schneider & McCarl, 2005;

Meng, 2015). In order to understand the potential effects of the carbon tax on emissions and agricultural production the following will summarize the findings of these articles.

In 2008, the Canadian province of British Columbia (B.C.) implemented a carbon tax. In 2012, carbon tax exemptions were created for certain agricultural sectors in response to concerns from the agricultural industry that the carbon tax increased costs of production for B.C. producers resulting in a comparative disadvantage. Rivers and Schaufele (2013) utilize a Heckscher-Ohlin model of comparative advantage to research this issue by analyzing the impact of a carbon tax in British Columbia on agricultural exports. Their findings contradict the theory that strict environmental policies would result in a comparative disadvantage for agricultural producers, as results indicate that a carbon tax of $20 resulted in exports rising by nearly 2%. The authors provide two possible explanations for this: 1) Agriculture in B.C. is not pollution-intensive but instead labor-intensive and thus the tax increases production of agricultural goods and 2) the tax may have encouraged innovation, resulting in B.C. producers having a comparative advantage over unregulated producers in pollution havens. Rivers and Schaufele (2013) concede that their results were derived using aggerate data instead of firm-level microdata which would likely result in more precise estimates (Rivers & Schaufele, 2013).

Olale, Yiridoe, Ochuodho, et al. (2019) conducted another study focusing on the carbon tax in the province of British Columbia. Olale, Yiridoe, Ochuodho, et al. (2019) applied a difference-in-difference method to estimate the effects of the carbon tax on farm income for agricultural producers in British Columbia. The authors conduct a sensitivity analysis for pre- and post-tax policy utilizing farm cash receipts, production costs and farm net income data for the period of 2000 to 2015. Olale, Yiridoe, Ochuodho, et al. (2019) finds that the carbon tax in British Columbia was associated with farm incomes decreasing by 8 – 12 cents per $1 of cash receipts. The authors attribute this decrease in farm income to higher feed costs, higher labor costs due to substituting away from capital that was fossil fuel intensive, higher interest costs from increased demand for operating loans to cover increased operating costs and higher depreciations costs from decreased value of farm assets (Olale, Yiridoe, Ochuodho, et al., 2019). In response to the work by Olale, Yiridoe, Ochuodho, et al. (2019), a comment was provided by Slade, Lloyd-Smith & Skolrud (2020) critiquing the data and difference in difference method used, especially the underlying assumption that, had the carbon tax in B.C. not been imposed, the difference in farm income between B.C. and the rest of Canada would have remained constant over time. Slade, Lloyd-Smith & Skolrud (2020) argue that due to commodity-specific shocks and different agronomic conditions in B.C. compared to the rest of Canada, this assumption is not likely to hold. The flaws in Olale, Yiridoe, Ochuodho, et al.'s research pointed out by Slade, Lloyd-Smith & Skolrud (2020) call into question the validity of the estimates derived from this difference in difference approach. As a result, Slade, Lloyd-Smith & Skolrud (2020) conclude that there is demand for further research investigating the effect of a carbon tax on the agricultural industry (Slade, Lloyd-Smith, & and Skolrud, 2020).

Schneider and McCarl's (2005) assessed the effects of a carbon tax on farm income utilizing a mathematical programming-based model. Their findings suggest there are only small loses to agricultural producers when carbon taxes are modest in the United States. In fact, their model indicates that when carbon taxes increase farmers receive benefits, as consumers bear the main burden of these taxes. The two main factors that drive these results are that: 1) As agricultural production becomes more costly as a result of the carbon tax, agricultural supply is reduced causing higher prices for agricultural commodities which results in higher revenues that offset the farm cost increases that result from the tax, 2) When production of biofuel feedstocks is a more profitable business opportunity as a result of the carbon tax, additional revenues will be generated for farms and the diversion of agricultural production to the bioenergy sector will further lower crop supply and further increase crop prices (Schneider & McCarl, 2005).

Schneider and McCarl's (2005) model also provides insight on how producers may change their management practices in response to a carbon tax. The net response is driven by two counteracting forces: 1) High energy prices promote management practices that use less energy including: reduced tillage, irrigation, and nitrogen fertilization, 2) High commodity prices promote yield-intensive management practices, which is conducive to higher input use. The net effect of these two counteracting incentives will determine producer's management response to the carbon tax. In Schneider and McCarl's (2005) model, if biofuel production is not profitable then management practices that are less energy-intensive prevail. As biofuel production increases in prevalence, management practices will shift back to input intensive management. Schneider and McCarl (2005) conclude that the implementation of a carbon tax does not necessarily lead to environmental co-benefits in U.S. agriculture and therefore such policies should be carefully studied (Schneider & McCarl, 2005).

Meng (2015) also utilized a computable general equilibrium (CGE) model to examine the effects of different carbon tax schemes on the agricultural industry in Australia. The authors include a scenario where the carbon tax is imposed on all emitters except agriculture and a scenario where a carbon tax is implemented directly on agricultural production. The results indicate that all agricultural sectors would be negatively affected by the carbon pricing policy. The authors note that even in the scenario where agricultural producers are exempted from a direct carbon tax, the indirect impact of the carbon tax through high energy costs will significantly impact agriculture. After the implementation of a carbon tax on the agricultural industry, their results indicate a decrease in output, employment, and profitability of the agricultural sector, but a much larger reduction in emissions. The authors conclude that overall, the carbon tax policy is effective in that it can greatly reduce emissions with only small effects on the overall economy (Meng, 2015).

Dumortier and Elobeid (2021) model the impacts of a carbon tax in the United States on agricultural markets and the resulting carbon emissions from land-use change. A global agricultural simulation model was utilized to assess the impact of the policy on agricultural production, commodity prices and trade. Dumortier and Elobeid (2021) further their analysis by quantifying the land-use change and resulting GHG emissions to assess the potential unintended consequences of increasing global emissions. The model included carbon pricing ranging from \$15 - \$144 t^{-1} of CO_2eq and covered a 10-year projection period. At the highest carbon price of \$144 t^{-1} of CO_2eq the net returns were decreased by 11.4%, 8.7%, 11.0% for corn, soybeans, and wheat respectively. The carbon tax resulted in altered trade patterns with a decrease in U.S. exports for corn (24.9%), sorghum (20.5%), and wheat (8.7%) while U.S. exports for barley, soybeans and sunflowers increased by 1.2-8.8%. The model results indicated a reallocation of land-use globally as a result of the changes in these trade patterns. The increased GHG emissions from land-use change was equivalent to 1.8% of the total U.S. emissions in 2017. The model results indicate the increase in emissions from land-use change due to changes in trade flow is small relative to the overall reduction in GHG emission form the carbon tax. However, the authors emphasize the importance of assessing potential leakage in the form of land-use changes, especially on carbon rich native vegetation (Dumortier & Elobeid, 2021).

2.2.4 Taxation of Nitrogen Fertilizer

As this thesis is focused on N_2O emissions from nitrogen fertilizer application, the following will overview previous research on policies that aim to reduce GHG emissions from nitrogen fertilizer application. Previous literature provides estimates of the GHG abatement cost as well as assessments of specific policies that reduce nitrogen application rates and apply taxes on N_2O emissions.

A previous study simulated the marginal abatement cost of nitrous oxide reductions from excessive nitrogen fertilizer applications in corn based on previous studies conducted in the Northern U.S. and Canada. Rosas et al. simulation produced results that with a $30 per ton of CO_2eq, a farmer reduces their nitrogen applications by roughly 4% as a result of an offset payment of $3.07/hectare. This reduced nitrogen fertilizer application has only a minimal expected yield penalty (less than 5%) because their focus was on nitrogen applications that are in surplus to the crops needs. Whereas a linear scheme aiming to achieve the same N_2O emission reductions would inadvertently require an N application reduction of 10% with an associated yield penalty of 2% (Rosas, Babcock, & Hayes, 2015).

Karatay et al. looked at the comparative advantages of mitigating greenhouse gas emissions by nitrogen fertilizer reduction over five yield zones in the state of Brandenburg, Germany for both wheat and rye. Over the range of 0-40 kg N/ha reduced rate from the economic optimum, the loss in net return pounds/ha ranged from 0-90. Their study included nitrous oxide emissions from both indirect (ammonification and leaching) and direct sources. Over the range of 0-40 kg N/ha reduced fertilizer rate from the optimum, the GHG mitigation cost lbs per tonne of CO_2eq ranged from 0-225 (Karatay & Meyer-Aurich, 2018).

Meyer-Aurich, Karatay, Nausediene & Kirschke studied the impacts of a fertilizer tax on nitrogen fertilizer use and mitigation of GHG emissions in Germany. Field experimental data was used to conduct production function analysis to compare the cost of GHG mitigation with different tax schemes ranging from £ 10 to 100 t^{-1} CO_2eq which was equal to £ 0.1 to 1.0 kg^{-1} N. Their results indicate that at moderate tax levels(£ 0.2 kg^{-1} N), nitrogen fertilizer application is reduced with GHG emissions costs below $100 t^{-1} CO2eq for rye, barley, and canola. However, in wheat production the tax on nitrogen had limited effects due to the large impact a reduction in nitrogen fertilizer in wheat production as crop quality, which affect the sale prices of wheat. The authors conclude that these results indicate that a moderate tax on nitrogen fertilizer can be effective in curbing GHG emissions at low costs by reducing nitrogen fertilizer use (Meyer-Aurich, Karatay, Nausediene, et al., 2020). Meyer-Aurich, Karatay, Nausediene et al. attribute the low GHG mitigation costs to the flat profit functions that are close to the economic optimum (Meyer-Aurich, Karatay, Nausediene, et al., 2020; Karatay & Meyer-Aurich, 2018). However, the different nitrogen fertilizer response of different crop types may have an impact on the relative advantage of such a policy, which should be taken into consideration when developing policy (Meyer-Aurich, Karatay, Nausediene, et al., 2020). The authors compare the estimated cost of GHG mitigation from a small nitrogen tax to previous findings by Smith et al., and conclude these are relatively low costs to reducing emissions and provides a good argument to consider nitrogen taxation (Smith, et al., 2008; Meyer-Aurich, Karatay, Nausediene, et al., 2020). However, the burden of the tax falls on producers which is much higher than the economic cost associated with reduced nitrogen fertilizer rates. The authors highlight the potential for the tax burden to be retransferred to producers through complimentary policies to reallocate the tax revenue generated (Meyer-Aurich, Karatay, Nausediene, et al., 2020).

Elobeid et al. analyzes policies aimed at mitigating the negative environmental impacts of increased agricultural production due to biofuel expansion. Biofuel expansion has been associated with negative environmental consequences that may offset the intended environmental benefits of biofuels including changes in land-use and land management practices as well as increased application of fertilizer (Elobeid, et al., 2013). Based on previous studies of the effect of uncertainty on optimal nitrogen applications by Babcock (1992), it has been found that US farmers may apply more nitrogen than they need in a typical year. The reason US farmers may overapply nitrogen is due to leaching in wet conditions which results in producers applying excess nitrogen to insure against wet spring weather (Babcock, 1992). The case of over-fertilization is of great environmental concern as nitrogen application rates that exceed agronomic recommendations drastically increase N_2O emissions (Elobeid, et al., 2013). Therefore, Elobeid et al. consider a scenario with a tax on nitrogen fertilizer in the United States by 10% over the baseline from 2011 to 2025. Overall, it is estimated that this tax on nitrogen fertilizer would reduce domestic fertilizer use by just under 0.2%. The results show that a tax on nitrogen fertilizer reduces the production of nitrogen-intensive crops such as corn, with a decrease in harvested area and nitrogen application rates. However, this reduction in US production of nitrogen-intensive crops is found to be partially offset by higher fertilizer use in other countries due to higher crop prices. The increase in global crop area in the world as a response to the nitrogen tax in the U.S. may result in increased in GHG emissions if the land conversion is from areas of sequestered carbon to cropland. As a result, overall the impact of the tax on GHG emissions is muted as the world market is allowed to adjust. The authors conclude from their findings that domestic policy changes implemented by a large crop producer such as the United States can significantly impact world commodity markets and may result in an unintended consequence of increased GHG emissions. The authors suggest that one way to prevent carbon leakage from unilateral policies is the international cooperation on environmental policies which is previously discussed in section 2.2.1 Carbon Leakage of this literature review (Elobeid, et al., 2013).

2.3 Nitrogen in Canola Production

Nitrogen is one of the main determinants of canola yield. The response function of canola to nitrogen fertilizer applied is dependent on soil available nitrogen. Soper (1971) investigated the effects of soil residual nitrogen on the yield response of canola to applied nitrogen. It was found that the canola yield response to nitrogen applied increases as soil test results of soil $N\text{-}NO_3$ levels decrease below 100 kg N ha^{-1} (Soper, 1971). A strong yield response to nitrogen has been found for canola in Saskatchewan, as most soils on the prairie of Canada are deficient in plant available nitrogen. Therefore, application of nitrogen fertilizer is required to grow high yielding canola (Grant & Bailey, 1993). Saskatchewan field trials have found the canola yield maximizing levels of available nitrogen ranging from 100 to 200 kg N ha^{-1} (Mahli, et al., 2007). In previous works, the canola yield response to applied N has often been modeled as a quadratic function (Brandt, et al., 2007; Cutforth, et al., 2009). Canola nitrogen response has also been found to be dependent on environmental conditions. Mahli et al. (2007) compared the nitrogen response of hybrid and open-pollinated canola varieties with rates ranging from 0-150 kg N ha^{-1} applied. This study found a strong interaction effect of nitrogen fertilizer with moisture. Under the moist conditions of 2000, canola yields were not maximized at the highest application rate of 150 kg N ha^{-1} while under the dryer conditions of 2001, canola yields were maximized at 118 kg N ha^{-1} applied (Mahli, et al., 2007). A summary of the canola response to nitrogen from Saskatchewan small-plot trials is shown in Table 1 which was adapted from the literature review compiled by (Assefa, et al., 2018)   and expanded on with additional literature sources.

Table 2-1: Canola yield response to nitrogen in Saskatchewan field studies.

Source	Source	Quadratic fit equations of yield response to nitrogen	R^2	Max. yield ***	N app rate at Max. yield ***	Location	Year	Notes
(Mahli, et al., 2007)	Graph, data	$Y= -0.034x^2 + 11.966x + 1656$	0.96	2.7	150+	Scott, IH, Melfort	2000	Hybrid, above-normal moisture
(Mahli, et al., 2007)	Graph, data	$Y= -0.05x^2 + 11.837x + 1011$	0.97	1.7	150+	Scott, IH, Melfort	2001	Hybrid, below-normal moisture
(Brandt, et al., 2007)	Data	$Y= -0.2059x^2 + 39.374x + 65.795$	0.20	2.6	110+	Scott	1999-2001	Hybrid
(Brandt, et al., 2007)	Data	$Y= -0.032x^2 + 8.515x + 1345.6$	0.33	2.1	137+	Melfort	1999-2001	Hybrid
(Brandt, et al., 2007)	Data	$Y= -0.0561x^2 + 11.504x + 1106.7$	0.17	2.1	139+	Indian Head	1999-2001	Hybrid
(Mahli & Gill., 2007)	Data	$Y= -0.0401x^2 + 4.7113x + 620.56$	0.05	1.7	100	Tisdale, AW, PP	1999-2000	Brassica napus rapa, 0 kg S ha^{-1}
(Mahli & Gill., 2007)	Data	$Y= -0.0324x^2 + 9.1038x + 646.44$	0.16	2.5	150+	Tisdale, AW, PP	1999-2000	Brassica napus, 30 kg S ha^{-1}
(Cutforth, et al., 2009)	Graph	$Y= -0.0228x^2 + 9.907x + 1232$	0.81	2.4	200	SC, Scott & IH	2000-2001 Scott & IH, 2000-2005 SC	Hybrid, semi-arid conditions
(Gan, et al., 2011)	Graph, data	$Y= -0.020x^2 + 8x + 1300$	-	1.7	135	Melfort, Saskatoon, Scott, SW	2003-2005	B. napus

Note: Table adapted from the literature review compiled by (Assefa, et al., 2018) and expanded on with additional sources
*** Max. yields and N rates reported based on Max. observed in the data, not based on quadratic fit
+ Indicates maximum yield was at the highest rate of N that was used in trial in a given year
Abbreviations: IH – Indian Head, SC – Swift Current, PP - Porcupine Plain, AW- Archerwill

2.3.1 Economic Optimal Nitrogen Fertilizer Use in Saskatchewan Canola

Mahli et al (2007) assessed the economic optimum for nitrogen fertilizer at different application rates. These calculations were based on the canola nitrogen response for the years 2000 and 2001 in field experiments from Melfort, Scott, and Indian Head. A range of canola prices from $200-400/tonne and fertilizer costs ranging from $500-1000/tonne of N were used in their analysis. The economic optimum for nitrogen applied ranged from 106-167 kg ha^{-1} in the moist conditions of 2000 and varied from 66-105 kg ha^{-1} under the drier conditions of 2001. Mahli et al. (2007) found that the estimated economic optimal nitrogen rates under moist conditions were higher than rates typically applied by Saskatchewan canola growers. Potential reasons for this discrepancy include canola producers managing their risk of adverse growing season conditions and/or unexpected changes in the sale price of canola. Another possible reason for observed nitrogen rates that are lower than the estimated economic optimum for canola is limited access to credit (Mahli, et al., 2007). Current agronomic nitrogen recommendations depend on target yields. According to the Canola Council of Canada, Canola needs 2.8 - 4 kg/ha of available nitrogen per 56 kg of seed yield (Canola Council of Canada, 2020). Agronomic nitrogen recommendations for a target yield of 2300 kg/ha yield takes up 115-164 kg/ha of nitrogen (Canola Council of Canada, 2020). Growers may differnt lower target N fertilizer levels than those recommended as a means of managing risk as described above (Mahli, et al., 2007).

2.4 Review of Other Factors that Affect Canola Production

While nitrogen is the factor of canola production that is the primary focus of this thesis, in the development of the canola production function an understanding of the range of agronomic factors that impact canola production is need. Asseffa et al. (2018) reviewed canola performance research trials across North America including peer-reviewed articles and extension works to assess the main management factors that impact yield. They found that the main determinants of canola yield include growing season precipitation water distribution at critical plant stages and nutrient supply (soil plus fertilizer). Other management factors that affect canola production include seeding rate, cultivar selection and crop rotation (Assefa, et al., 2018). Asseffa et al. 2018 provide a theoretical framework of the factors that determine canola yield and their significance according to papers reviewed. Resource factors from highest to lowest are rainfall, latitude/radiation, soil properties/nutrients/fertilizer, temperature, and length of growing season. Management factors listed in highest to lowest significance: seeding date, planting depth, seeding rate, rotation/residue/tillage, cultivar, herbicide/seed treatment (Assefa, et al., 2018). The following is a literature review of the main factors that in addition to nitrogen that affect canola production categorized into management and environmental factors.

2.4.1 On-Farm Canola Management Decisions

There have been numerous previous works that studied various management factors such as fertility, seeding rate, herbicide use, variety, etc. and their impact on canola production in Saskatchewan. These studies mainly use factorial experimental plot design with many of these studies performed over more than one year and at multiple locations. The management factors that impact canola production are numerous. In assessing the factors that affect canola production, Liu et al., (2014) makes the case that a systems approach with multiple factors integrated may be needed to explore the yield potential of canola. However, Liu et al (2014) also acknowledges that the cost of studying multiple factors in an experimental field study across multiple locations and years would be very costly (Liu, Gan, & Poppy, 2014). An alternative to an experimental field study is to collect data from farm fields to analyze the management practices in-use by canola producers. Liu et al. (2014) employed this on-farm approach from 2010-2011 on 68 canola fields across Alberta, Saskatchewan, and Manitoba. Researchers went out to each field and collected in-depth information for each field including measuring seedling emergence, seeding depth, soil moisture, etc. Their study aimed to identify the agronomic factors that impact canola yields across different soil zones. The key findings of Liu et al. (2014) suggest that there are a number of management practices and farm characteristics that significantly affect canola yields including: preceding crop, previous crop, seeding date and row spacing. Variables in order of their VIP values which indicates importance to yield are: seeding rate, sulphur fertilizer, seeding depth, days to harvest, previous crop yield, row spacing, previous crop height, days to seeding after April 25, nitrogen fertilizer rate, seeding speed, plant density and phosphorous fertilizer rate (Liu, Gan, & Poppy, 2014). The following is a review of the factors that impact canola production from small-plot field studies with the exception of the Liu et al., 2014, which is an on-farm study.

2.4.2 Seeding Date

Studies have shown that seeding date of canola is another important management factor of yield. Mackenzie et al. (2011) studied the optimal seeding date in irrigated canola in southern Alberta. Their results indicate that early spring seeded canola is advantageous as the reproductive stages of canola are highly heat-sensitive. Earlier planting allows reproductive canola development to take place earlier in the growing season, when air temperatures are likely cooler. MaKenzie estimates a 1.7% decrease in yield per day of delayed seeding from April 30th (McKenzie, Bremer, Middleton, Pfiffner, & Woods, 2011). Angadi et al. (2004) also assessed the impact of seeding date on yields in Swift Current, Saskatchewan from 1999-2001 and found that most often earlier seeded spring canola was the highest yielding relative to later planting (Angadi, Cutforth, McConkey, & Gan, Early seeding improves the sustainability of canola and mustard production on the Canadian semiarid prairie, 2004). This finding that earlier seeding increases canola yields is similar to the findings of the on-farm study conducted by Liu et al., 2014 in the western provinces (Liu, Gan, & Poppy, 2014). However, earlier seeding date may not always be a simple linear relationship with yield. The soil moisture of the spring is a critical factor that impacts early canola establishment. Seeding early-mid spring was found to be best under moist spring conditions. However, under dry spring conditions, mid-late spring-seeding was best (Angadi, Cutforth, McConkey, & Gan, 2004). Temperature conditions of the spring is another critical factor that has been found to effect canola establishment. Planting earlier in the season includes colder soil temperatures which may impact germination and emergence (Assefa, et al., 2018; Pavlista, Isbell, Baltensperger, & Hergert, 2011). In an assessment of the interaction between seeding date and crop yields in canola in Saskatchewan, Catellier (2022) found with seeding dates ranging from May 1 to June 15, the optimum seeding date was mid-May across all environments. This report found that canola yield losses increased as the seeding date moved further away from the optimum (Catellier, 2022).

2.4.3 Crop Rotation

Crop rotations of 3 - 4 years are recommended (Kutcher, et al., 2013) and previous works have found that a 3-year crop rotation can increase canola yields relative to monocropping by as much as a 22% (Harker et al., 2015). This increase in canola yields from crop rotation is unsurprising as previous literature has found increased crop rotation diversity reduces soil borne pathogens (Hwang, et al., 2019), incidence of blackleg disease (*Leptosphaeria maculans* Desmaz.) (Kutcher, et al., 2013; Marcroft et al., 2012), weed pressure (Blackshaw, et al., 2010) while enriching soil microbial functional diversity and enzyme activity (Lupwayi, et al., 2007). The species of crops in rotation also have been found to impact canola yield, with nitrogen fixing legumes such as field peas and lentils having been found to boost canola yields compared to non-legumes such as cereals (O'Donovan, et al., 2014). Previous findings of rotational benefits of pulse crops that boost subsequent yields include increase soil available nitrogen (O'Donovan, et al., 2014), higher residual soil moisture (Elliot, Papendick, & Bezdicek, 1987), more rapid N mineralization in residues of higher N concentration (Janzen & Kucey, 1988; Sandford & Hairston, 1984), pulses producing a loose, mellow soil surface (Moldenhauer, et al., 1983) and a lower C:N ratio in soil organic matter after legumes (Hargrove, 1986). Previous studies have found that canola grown on chem fallow produces 17% higher yields relative to canola grown on cereal previous crop, which is likely due to chem fallow preserving soil moisture. This same study found that canola grown as a monocrop produced 54% of the yields of canola grown on cereal previous crop (Lafond & Derksen, 1990).

2.4.4 Phosphorous, Sulphur, and Potassium

After a thorough literature review of canola studies in North America, Aseffa et al., 2018 found that a canola plant takes up 62–12–45–28 kg of plant N–P–K–S / t yield (Assefa, et al., 2018). In Liu et al (2014) on-farm western Canada study, it was found that found that canola receiving potassium fertilizer increased seed yield relative to no potassium fertilizer applied by 25%. This same study found that with each kg increase in S fertilizer, there was a corresponding increase in seed yield by 19 kg/ha, with applications in the 15-30 kg/ha range for sulphur appearing adequate to prevent it from being a limiting nutrient for canola (Liu, Gan, & Poppy, 2014). This canola response to sulphur is similar to the previous findings of (Mahli & Gill., 2007). Malhi and Gill (2007) found evidence of an interaction effect of nitrogen fertilizer with sulphur fertilizer in sulphur deficient gray luvisol soils in Northeastern Saskatchewan. Their field study indicates that sulphur is required to meet the nutrient requirements on these S-deficient soils for optimum yields at high nitrogen rates (Mahli & Gill., 2007).

2.4.5 Fungicide

The impact of application of fungicides to combat diseases in canola have been studied in a variety of environmental conditions. Previous studies have observed a significant yield benefit from fungicide application in canola when disease incidence is high. Kutcher and Wolf (2006) found a benefit to fungicide application when stem rot levels varied from 30 to over 50% in the untreated control (Kutcher & Wolf, 2006). However, Harker et al., 2011 found fungicide was beneficial to canola yield in one out of two years, even with minor incidence of disease (Harker, et al., 2011). Conversely, Brandt et al., 2007 found no benefit of fungicide application (Brandt, et al., 2007).

2.4.6 Weed Control and Herbicide Tolerant Varieties

Canola hybrid varieties have been bred for different herbicide-tolerance. The herbicide-tolerance trait of canola varieties has been used to reduce weed pressure which can significantly increase yields (Harker, Blackshaw, Kirkland, et al., 2000; Harker, O'Donovan, Clayton, et al., 2008; Clayton, Harker, O'Donovan, et al., 2002). Liu et al., 2014 found that pre-seed herbicide applications of glyphosate tank mixed with MCPA increased canola yields by 35% relative to fields only using glyphosate or no herbicide (Liu, Gan, & Poppy, 2014). Liu et al., 2014 found that cultivars with the Liberty Link herbicide system were the highest yielding on aggregate relative to Round-up Ready system, with a 700 kg/ha increase in yield (Liu, Gan, & Poppy, 2014).

2.4.7 Seeding rate and Plant Density

The management factor of seeding rate contributes to overall plant density of canola. There have been numerous studies on the effects of seeding rate and plant density on canola yield. In comparing these studies, it appears that the effect of canola plant density on yield is largely contingent on the environmental conditions (Assefa, et al., 2018). Canola is a highly elastic plant under favourable environments which means canola plants can produce additional branches to compensate for low-density plant populations. Conversely, under unfavourable growing conditions including biotic and abiotic stress, canola plants are less able to compensate for low-density plant populations through increased branching (McGregor, 1987; Morrison, 1990). This may explain the range of previous findings of the effect of seeding rate on canola yield compiled by (Assefa, et al., 2018) which include: positive (Clarke & Simpson, 1978; Harker, Clayton, Blackshaw, et al., 2003; Brandt, et al., 2007; Hanson, Johnson, Henson, et al., 2008) negative (Kondra, 1975), no-effect (Degenhardt & Kondra, 1981; Christensen & Drabble, 1984; Angadi, Cutforth, McConkey, et al., 2003) and site-specific (Kondra, 1977; Gan, et al., 2016).

The on-farm study of Liu, Gan, and Poppy (2014) supports the idea that seeding rate effects on canola yield are dependent on environmental conditions. Liu, Gan, and Poppy (2014) found that seeding rate was found to be negatively correlated with seed yield (Liu, Gan, & Poppy, 2014). This finding is in contrast to previous experimental studies that have found that increasing seeding rate increases canola yield (Angadi, Cutforth, McConkey, et al., 2003; Harker, Clayton, Blackshaw, et al., 2003; Brandt, et al., 2007; Hanson, Johnson, Henson, et al., 2008). This was because producers in the brown soil zone typically had higher seeding rates for canola, as their emergence is often in the 30-50% range due to the often-stressful weather conditions in this drier area. Liu, Gan, and Poppy (2014) conclude that using plant density is a more accurate determination of canola yield as opposed to seeding rate. Applying the same seeding rate across the different soils zones will likely result in differing plant populations in the brown soil zone vs. the black soil zone (Liu, Gan, & Poppy, 2014).

2.4.8 Row-spacing

There have been several studies that examine the effects of row spacing on canola yield on the Canadian prairies. Hu et al. (2015) conducted field trials of row spacing in canola at Central Butte and Swift Current, Saskatchewan. Two row spacings of 30 cm and 60 cm were tested, with 30 cm row spacing overall increased yield, soil water content and water use efficiency for most years and site combinations (Hu, Schoenau, Cutforth, et al., 2015). Similarly, Kutcher et al. (2013) and Liu, Gan, and Poppy (2014) found canola yield increased with narrower row spacing at sites across the Canadian prairies (Liu, Gan, & Poppy, 2014; Kutcher, Turkington, Clayton, et al., 2013). Overall, narrower row spacing is recommended for higher yielding canola on the Canadian prairies.

2.4.9 Tillage/Residue Management

Previous literature has not found a significant effect of tillage systems on canola yield when comparing no-till, minimum-till and conventional systems (Assefa, et al., 2018; Azooz & Arshad, 1998; Clayton, Harker, O'Donovan, et al., 2002; Holman, Maxwell, Stamm, et al., 2011). Previous studies have found an increase in canola yields with no-tillage relative to pre-seed tillage, however the effect was marginal (p=0.07) (Liu, Gan, & Poppy, 2014). However, residue can have an important impact on canola emergence and yield. Previous works have found that dense, unbroken residue in a no-tillage system can reduce canola emergence and ultimately yield (Soon, Klein-Gebbinck, & Arshad, 2005). In contrast, other works have found that tall previous crop can reduce frost damage (Volkmar & Irvine, 2005).

2.4.10 Seeding Depth and Method

A variety of seeding methods have been researched including the impact of planter speed, packing wheel pressure, and seeding depth on canola yields. Thomas, Raymer & Breve (1994) conducted a study in Southeastern USA and found that packing wheel pressure impacted emergence but did not ultimately effect canola yield. Increasing planting speed was found to decrease emergence, while packing wheel pressure had different effects depending on the soil type. Thomas, Raymer & Breve (1994) also studied the effect of seeding depth on yield, with depths ranging from 0.25 – 2 inches. There was only a significant effect of seeding depth on plant density in 1/3 years. It was found that shallower seeding depth is preferred to deeper seeding depth, with the quadratic effect indicating that the optimal seeding depth was 0.5 inches (Assefa, et al., 2018; Thomas, Raymer, & Breve, 1994). Several other studies have found a similar result of increased seeding depth decreasing yield relative to shallow seeding (Liu, Gan, & Poppy, 2014; Hanson, Johnson, Henson, et al., 2008; Harker, et al., 2012). Harker et al. (2012) studied the effect of seeding depth and speed on hybrid canola grown at Lacombe, AB, Lethbridge, AB, Indian Head, SK and Scott, SK over the years 2007-2010 with a total of 16 site-years. When comparing seeding depths of 1 vs 4 cm there was no significant impact on canola yield. However, under moist conditions canola emergence density increased from 36 to 62% when seeding depth is reduced from 4 to 1cm. Harker et al. (2012) also compared seeding speeds of 6.4 vs. 11.2 kg h^{-1} and found no significant impact on yield. A higher seed speed tended to reduce emergence density of canola (Harker, et al., 2012). From the rates studied in previous research, packing pressure, seeding depth, and seeding speed may not have significant impacts on canola yield. However, shallow seeding depth and slow seeding speeds can increase canola emergence which can improve the survivability success rate of canola under conditions of environmental stress (Thomas, Raymer, & Breve, 1994; Harker et al., 2012).

2.4.11 Environmental Conditions

Canola yields are greatly impacted by environmental conditions including precipitation, temperature, and annual variation in growing conditions. When aggregating performance trial data across North America, Assefa et al. (2018) found that proper quantities of precipitation and timing of available water is a large determinant of canola yield. An average yield gain of 7.2kg ha^{-1} was found for each millimeter of water between 125-600mm (Assefa, et al., 2018). Previous works have supported this finding that excessive or limited precipitation can reduce crop yields in the form of reduced growth, disease pressure and reducing plant available nutrients (Franklin, Kav, Nate, et al., 2005; Bedard-Haughn, 2009). During canola's reproductive stage or flowering period, high temperatures increase fruit abortion (Gan, et al., 2004) which results in reduced yield (Kutcher, Warland, & Brandt, 2010). A study by Harker et al., 2011 supports this finding, as their results also indicate a negative correlation between canola yields and high temperatures. High yielding canola was positively correlated with soil organic matter and growing season length (Harker, et al., 2011). The yield response to nitrogen application changed based on the variation in annual growing conditions (Angadi, Cutforth, McConkey, et al., 2004; Gan, et al., 2004; Henry & MacDonald, 1978).

2.5 Chapter Summary

To combat climate change, environmental policy is needed to combat the negative externality of pollution. The economic literature surrounding the impacts of a carbon tax on the agricultural industry is inconclusive regarding the effect on farm incomes and agricultural exports. There has been limited studies on the GHG mitigation cost of nitrogen in a Canadian context. However, previous research in Europe has found that a small nitrogen tax may produce relatively low costs to reducing emissions and provides a good argument to consider nitrogen taxation (Meyer-Aurich, Karatay, Nausediene, et al., 2020). Further research is needed regarding this policy, especially regarding nitrous oxide emissions from nitrogen fertilizer, as federal government have announced targets of reducing fertilizer application GHG emissions by 30% from 2020 levels by the year 2030. Many Saskatchewan studies have focused on the factors that affect the production of the nitrogen intensive crop canola. Nitrogen has been found to be a large determinant of canola yields. However, few studies have used on-farm producer data to assess the canola nitrogen response curve. No studies were found that use on-farm data to assess the economic optimum for nitrogen fertilizer application in the context of Saskatchewan.

CHAPTER 3 CONCEPTUAL FRAMEWORK AND METHODOLOGY

3.1 Introduction

This chapter details the conceptual framework and methodology used to estimate the economic optimal applied nitrogen rate and assess different environmental policy scenarios for nitrogen fertilizer use. The economic optimal for nitrogen application in canola will be estimated from producer reported field-level management data over multiple years and a wide range of climatic and spatial conditions. The estimated canola yield response to nitrogen fertilizer will then be used to estimate the effects of reduced fertilizer levels and a N_2O taxation policy on net return and GHG emissions. The first part of this chapter explains the theory for optimal nitrogen use followed by an explanation of the production function estimation and econometric techniques used. This is followed by an explanation of the approach used in the environmental policy simulations including estimating N_2O emissions associated with nitrogen application and methodology used for estimating GHG mitigation costs, the post N_2O tax economic optimal applied nitrogen rate, net return and GHG emissions.

3.2 Theory for Optimal Nitrogen Use

3.2.1 Assumptions for Optimal Nitrogen Use

In estimating the optimal nitrogen application rate in Saskatchewan canola several assumptions are made. First, Saskatchewan canola producers are assumed to be profit maximizing. Secondly, it is assumed that producers are risk neutral in the decision-making process of fertilizer application. The estimation of the optimal nitrogen fertilizer application rate is conducted in the short-run and therefore it is assumed that fixed inputs are held constant. It is assumed that canola variety is fixed in the short-run based on the assumption that variety selection decisions are made independent from and made prior to nitrogen fertilizer use decisions. The previous crop type (pulse, oilseed, or cereal) of a field is also assumed to be fixed in the canola production system in the short run but can be changed in the long run. Since the optimal nitrogen rate is the focus of this thesis, consideration must be given to the potential for producers to substitute away from nitrogen use. For example, under a tax on nitrogen fertilizer in the long-run producers may substitute from growing canola to a crop that requires less nitrogen applied such as a pulse crop. However, this analysis is focused on the short run scenario and therefore the potential for producers to substitute to less nitrogen intensive crops is not considered within the model. It is also important to consider the relationship between nitrogen and other inputs within the canola production function, and whether they are substitutes, compliments or independent. Therefore, the relationship between nitrogen and other inputs in the canola production function will be tested empirically. The relationship between nitrogen and other canola production inputs will be explored by estimating various interaction terms within the model which is outlined in section 5.2 The Estimation Process.

3.2.2 Canola Production Function

The canola production function model is based on the agronomic theory that canola yields are a function of variable inputs, management factors and agro-ecological conditions. In equation 3-1, the yield of a canola field *i* at time *t* is a function of several vectors,

3-1

$$\gamma_{it} = f(v_{it}, x_{it}, z_{it})$$

where v_{it} is a vector comprised of variable inputs including fertilizer applied and fungicide applied. The vector x_{it} is comprised of management factors including crop rotation, variety chosen and seeding date. A vector of agro-ecological conditions is denoted by z_{it} which includes growing season precipitation, soil moisture, soil productivity and grain cropping risk zone.

3.2.3 Profit Function

The profit function is based on producer’s expectations of canola prices, and thus is an expected profit function. From the production function the expected profit function for canola production can be written as equation 3-2,

3-2

$$\mathrm{E}[\pi_{it}(p_t, w_t,\ r_t, v_{it}, x_{it})] = \mathrm{E}[p_t]\ * f(v_{it}, x_{it}, z_{it}) - \ \sum(w_t * v_{it}) - \sum(r_t * F_{it})$$

where the scalar p is the price of the output of canola, which is based on the producer's expectation of canola prices. The vector w contains prices for variable inputs, and r is a vector containing prices for fixed inputs. The vector F is comprised of fixed inputs. Profit (π) from canola production in is equal to revenue minus the sum of costs.

3.2.4 *Profit maximization*

Assuming that a producer's goal is to maximize expected profits of each individual field in each year, in the short-run producers will choose variable inputs to maximize expected profit as described by equation 3-3,

3-3

$$\mathrm{E}[\pi_{it}(p_t, w_t, v_{itj})] = \max_{v_{itj}}\ \mathrm{E}[p_t] * f\big(v_{itj}\big|\ v_{it}, x_{it}, z_{it}\ \big) - \ \sum(w_t * v_{it}) - \sum(r_t * F_{it})$$

where the subscript *j* identifies a specific variable input and production of canola is dependent on the variable inputs chosen in a specific field in a specific year. It is assumed that in the short run, a producer will optimize by choosing only variable inputs (v_{it}) for each individual field in a given year, while management factors (x_{it}) are fixed for each individual field within a year. In the short run, fixed inputs (F_{it})are also fixed for each individual field within a year.

3.2.5 *First Order Condition*

The first order condition of the short run profit maximization problem is shown in equation 3-4 where,

3-4

$$\frac{\partial \mathrm{E}[\pi_{it}(p_t, w_t, v_{itj})]}{\partial v_{itj}} = \max_{v_{itj}}\ \mathrm{E}[p_t] * f'^{(v_{itj}|\ v_{it}, x_{it}, z_{it}\,)} - \ w_{tj} = 0,\ \text{for all}\ j \in 1, \dots, n$$

the first order condition is derived by taking the partial derivative of expected profit with respect to each of the variable inputs. Within each year (*t*) the number of first order conditions (*n*) is equal to the number of fields (*i)* by the number of variable inputs *(j).*

3.2.6 Optimal Condition for a Variable Input

Using the first order condition 3-4, the optimal condition for a specific variable input nitrogen $(j = N)$ can be derived as shown in equation 3-5.

3-5

$$\mathrm{E}[p_t] * f'_{V_{itN}}(v_{itN} | v_{it\ j \neq N}, x_{it}, z_{it}) = w_{tN},\ j = N$$

The optimal condition for a variable input can be re-written as equation 3-6 and 3-7 where the optimal condition for nitrogen is where the expected value of the marginal product $(VMP_{V_{itN}})$ is equal to the input cost of nitrogen (w_{tN}).

3-6

$$\mathrm{E}[p_t] * \mathrm{E}\,[\mathrm{MP}_{V_{itN}}] = w_{tN}$$, further simplifying,

3-7

$$\mathrm{E}[VMP_{V_{itN}}] = w_{tN}$$

The optimal conditions for a variable can be rewritten where the expected input output cost ratio (CR_t) is equal to the expected $MP_{V_{itN}}$ as shown in equation 3-8 which will be used to estimate the economic optimal nitrogen rates for canola in Saskatchewan.

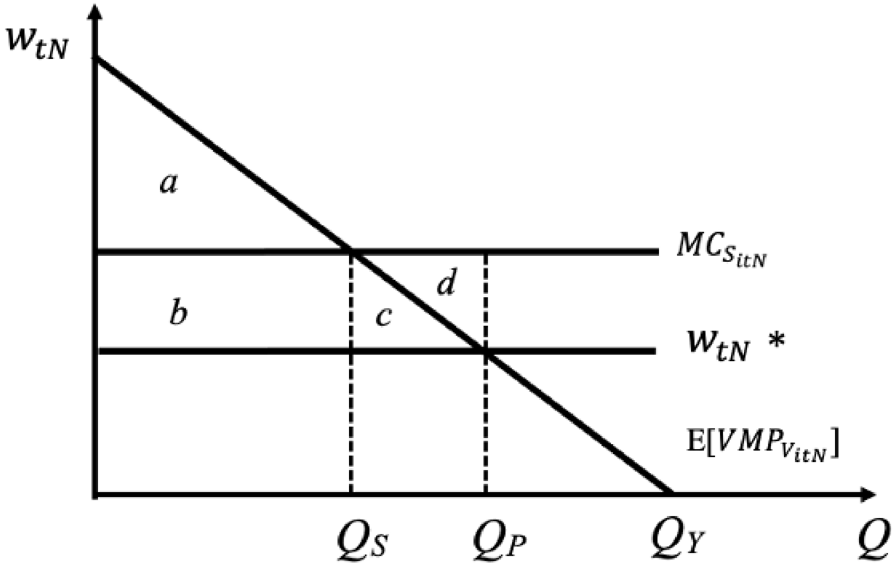
3-8

$$\frac{w_{tN}}{\mathrm{E}[p_t]} = \mathrm{E}[CR_t] = \mathrm{E}[MP_{V_{itN}}]$$

3.2.7 Graphical Representation of Optimal Nitrogen Use

The economic optimum for nitrogen fertilizer use can be depicted in graphical form, as shown in Figure 3-1. The per unit cost of nitrogen fertilizer in a given year (w_{tN}) is along the vertical axis while quantity of fertilizer applied (Q) is along the horizontal axis. The expected value of marginal product of nitrogen fertilizer in an individual field and year $(VMP_{V_{itN}})$ is a function of the expected canola price and expected marginal product of nitrogen as shown in equation 3-6. Due to the social cost of carbon associated with nitrogen fertilizer application, there is a marginal social cost of nitrogen application which is denoted by $MC_{S_{itN}}$ The per unit cost of nitrogen is w_N. The privately optimal rate of nitrogen applied is where E[$VMP_{V_{itN}}$] intersects with $w_{tN}*$ at Q_P. This would result in the maximum producer surplus equal to the area $a + b + c$. The external costs at Q_P are equal to the area *d*. The socially optimal rate of nitrogen applied is where $MC_{S_{itN}}$ intersects with E[$VMP_{V_{itN}}$] at Q_S. Yields are maximized at nitrogen rates of Q_Y.

Figure 3-1 Graphical representation of the theory of optimal nitrogen fertilizer use.



3.2.8 Logistical Constraints

While producers are interested in maximizing returns, the actual applied rate of a variable input may differ from the optimal condition shown in equation 3-7. One potential reason why producers may apply variable inputs at rates other than the profit maximizing optimal rate is experimentation. Producers may wish to verify that their applied rates are optimal by intentionally varying the applied rate of nitrogen across fields. Due to the evolving recommended nitrogen rates by agronomists in Saskatchewan and the improvement of canola varieties over time, experimentation by producers to find the optimal nitrogen rate may be observed. Another reason that producers may apply variable inputs at rates other than the profit maximizing optimal rate are logistical constraints. In the case of nitrogen fertilizer, due to the importance of timeliness at seeding where producers have a small window of time to get the crop sown, there are often constraints on time in hauling and applying nitrogen. Producers may apply nitrogen at rates based on the given constraint of available time and labour. Additionally, applying the intended rate of fertilizer can be challenging for several reasons including incorrect calibration, mechanical issues, and inaccurate estimates of seeded area. Since nitrogen is costly to procure and to store, producers will often adjust their rates on the remaining acreage to use their inventory. In the case of dry fertilizer, this may be particularly likely to occur as long-term storage may be a challenge. The cost of either quickly procuring more fertilizer or the cost of storage will be reflected in the optimal application rate for the remaining fields. In this case, variable inputs are optimized subject to a constraint due to restrictions that limit the quantity of variable inputs applied. Assuming that a producer's goal is to maximize expected profits subject to a constraint on variable inputs, in the short-run a producer will choose to optimize variable inputs as described by equation 3-9

3-9

$$\mathrm{E}[\pi_{it}(p_t, w_t, v_{itj})] = \max_{v_{itj}} \mathrm{E}[p_t] * f\big(v_{itj}\big|\, v_{it}, x_{it}, z_{it}\big) - \textstyle\sum(w_t * v_{it}) - \sum(r_t * F_{it})$$

$$s.t.\ \bar{v}_{itj} \geq v_{itj}$$

where a variable input (*j*) is optimized subject to a constraint due to time and logistical restrictions that limit the quantity of variable input applied within an individual field (*i*) in a given year (*t*) to the quantity ($\bar{v}$). Equation 3-9 can be rewritten as equation 3-10

3-10

$$\mathrm{E}[\pi_{it}(p_t, w_t, v_{itj}, \lambda_{itj})] = \max_{v_{itj}} \mathrm{E}[p_t] * f\big(v_{itj}\big|\, v_{it}, x_{it}, z_{it}\big) - \textstyle\sum(w_t * v_{it}) - \sum(r_t * F_{it}) + \lambda_{itj}(\bar{v}_{itj} - v_{itj})$$

which can then be used to derive the optimal conditions in the short run for a variable input under a constraint using the first order condition. This is written as equation 3-11

3-11

$$\mathrm{E}\big[VMP_{V_{itN}}\big] = w_{tN} + \lambda_{itN}$$

where the optimal condition for the variable input nitrogen is where the expected value of the marginal product ($VMP_{V_{itN}}$) is equal to the input cost of nitrogen (w_{tN}) plus the shadow value of any field specific application constraint (λ_{itj}). In the absence of any binding field specific variable input constraint, the optimal condition takes on the familiar form of equation 3-7.

3.3 Production Function Estimation

3.3.1 Functional Form

The functional form chosen to model the canola production function is very important to produce unbiased estimates for calculations of the optimal nitrogen fertilizer rates. A wide range of functional forms for yield response to fertilizer application have been used in the literature including quadratic, square root, exponential (Mitscherlich), and von Liebig models. The von Liebig model is based on the plant limiting nutrient principle where plants need complete combinations of inputs to grow. However, previous literature has suggested that even if plants are abiding by the limiting nutrient principle at the homogenous plot level, data on a field-scale level with heterogeneity results in a smooth aggregate production function (Berck & Helfand, 1990). When assessing production over a larger area, such as a field, farm or country level, heterogeneity of inputs or residual fertility occurs. For example, different plants in different parts of a field will be limited by different inputs such as water, soil productivity, fertilizer, etc. (Berck & Helfand, 1990). Based on the findings of Berck & Helfand (1990) and the data set used in this thesis of aggregated field-scale data over the wide area of the province of Saskatchewan, a smooth production function was chosen over a von Liebig model (Berck & Helfand, 1990). Previous statistical models that assess crop yield response to nitrogen have included square root, exponential and squared models (Bélanger, Walsh, Richards, et al., 2000; Khoshgoftarmanesh, Rafie, Zare, et al., 2022; Xia & Yan, 2011). As such, models that included each the square root, exponential and squared nitrogen terms were explored in the development of the canola production model for this thesis. The quadratic functional form is often used in agronomic literature to describe yield response to fertilizer application as it allows for diminishing returns, concavity, and substitution (Sheahan, Black, & Jayne, 2013). Previous findings in Saskatchewan agronomic literature have indicated a quadratic relationship between nitrogen and canola yield (Brandt et al., 2007; Cutforth et al., 2009; Gan et al., 2011; Mahli & Gill, 2007; Mahli et al., 2007). Ultimately, the quadratic functional form was chosen to model canola yield response to nitrogen based on previous agronomic studies and the estimation of more reasonable economic optimal nitrogen applied rates relative to the exponential or square root models.

3.3.2 Econometric Methods

The canola production function was modelled with a quadratic functional form with fixed effects of soil class, risk zone and producer by year. The model was estimated using ordinary least squares (OLS) with heteroskedasticity-robust standard errors (Wooldridge, 2010). The development of the canola production function model was based on previous literature on the factors that affect Saskatchewan canola production. Additionally, the econometric model developed by Sheahan, Black and Jayne (2013) to estimate the marginal and average products of nitrogen in the context of corn in Kenya was relied upon as a starting framework (Sheahan, Black, & Jayne, 2013). The panel dataset used to estimate the canola production function is a very large data set including producer reported information on observable variables including variable inputs, some agro-ecological factors, and some management decisions. The inclusion of variables in the canola production function were based upon data availability and canola agronomic theory which was reviewed in section 2.3. Interaction terms between nitrogen and other inputs in the canola production function were estimated to assess the validity of the assumption that nitrogen is not substitutable for another input in the short run. Additionally, various interaction terms were tested for inclusion in the model based on agronomic theory and statistical significance.

Due to the limited availability of data on the numerous variables that affect canola yield, fixed effects were utilized within the model. The canola production model utilizes fixed effects to control for unobserved heterogeneity across soil capability, region, and producer by year. Year fixed effects were included in the model to control for temporal variation in canola yields that are not otherwise accounted for in the model. Due to the unobserved effect of spatial factors on canola yield, such as the variation in growing conditions across regions, the grain cropping risk zones were included as fixed effects in the model. Unobserved heterogeneity across different soil capabilities was controlled for by including soil class fixed effects. Finally, producer by year fixed effects are included in the model to control for variation in canola yields among producers across time that are otherwise unobserved. The unobserved effect of an individual manager's skill by year likely has a significant impact on canola yield. However, by including the producer by year fixed effect, the source of variation of nitrogen rates by individual producers within years is assumed to be due to exogenous factors rather than endogenous factors. As described in equation 3-3, the theory for optimal nitrogen application in canola is assumed to be constrained due to time and logistical constraints at seeding which may be one source of exogenous variation of nitrogen rates by producers within years. A complete discussion of the issues regarding this assumption is provided in section 5.2 The Estimation Process. Additionally, results of alternative models where this assumption is relaxed are reported and discussed to assess the robustness of the estimates derived from the chosen model.

The estimated canola production model utilizes fixed effects to control for unobserved heterogeneity across groups of soil class, producer by year, and risk zone. As discussed by Levinsohn & Petrin (2003), this model protects against potential correlation between unobserved producer-specific fixed effects, such as managerial quality, and input choices using the variation within-firm. However, the between-producer variation may be important in estimating the output elasticities associated with variables that only change gradually over time, otherwise known as state variables (Levinsohn & Petrin, 2003). While the fixed effect models used in this thesis defends against producer-specific effects, in the case of correlation between input levels and unobserved time-varying producer-specific shocks, the estimates of this production function will be biased. For example, a producer that encounters a large positive productivity shock may respond by using more inputs (Levinsohn & Petrin, 2003). Several previous works have researched the effects of different estimators that address this problem and control for correlation between input levels and unobserved producer-specific productivity shocks.

Alternative methods to the OLS, IV or fixed effects estimators include the investment proxy estimator from Olley and Pakes (1996) which was further developed into an intermediate input proxy by Levinsohn & Petrin (2003) (Olley & Pakes, 1996; Levinsohn & Petrin, 2003). When proxying for the unobserved productivity shock is done correctly, the advantage over fixed effects estimators is that this methodology does not reduce the productivity shocks to a fixed over time producer effect (Griliches & Mairesse, 1998). Levinsohn & Petrin (2003) compare the estimates between the alternative econometric models of OLS, fixed effects, Blundell-Bond GMM estimator (a lagged-input instrumental variables estimator with fixed effects), Olley-Pakes investment proxy estimator and an intermediate input proxy estimator. Their findings indicate that the estimation of the production function using an intermediate input proxy differ from those estimated using either OLS, IV or fixed effects models. The results from the intermediate input proxy estimator also differed to a lesser extent from those of the Olley-Pakes investment proxy estimator (Levinsohn & Petrin, 2003). Previous research has aimed to develop alternative methods to address the issues of simultaneity in production functions. However, the employment of an investment proxy estimator or intermediate input proxy estimator was not employed in the development of the canola production function in this thesis due to a lack of available data. Therefore, the estimated results are reported with the important limitation that the estimation of the canola production function using fixed effects does not fully address the simultaneity problem (Levinsohn & Petrin, 2003).

3.3.3 Identification Assumptions

In the estimation of the canola production function, several assumptions are made. It is assumed that farmers make the decision of nitrogen fertilizer rate at the beginning of the growing season before exogenous shocks occur (lack of rainfall, pest infection, etc.). It is assumed that the average previous three-year historical growing season precipitation is a reasonable proxy for soil moisture. The assumption is also made that the production function is known to producers as they have expectations about input responsiveness and yields based on previous experience. Therefore, production management decisions are made uniquely by the producer for each field. The above section has focused on the theory of production function estimation, including identification assumptions, econometric methods, and functional form. The next section of this chapter will focus on the theory used for the environmental policy simulations.

3.4 Theory for Environmental Policy Simulations

3.4.1 Overview of GHG Accounting System

In order to combat climate change, an accounting system for anthropogenic GHG emissions must be used to assess trends and create policies. The United Nations Framework Convention on Climate Change (UNFCCC) and members of the Kyoto Protocol, such as Canada, are required to estimate and report National GHG Inventories (Rochette, et al., 2008). The Intergovernmental Panel on Climate Change (IPCC) provides a methodological approach to estimate emissions from agricultural soils. Under the IPCC accounting system, the nitrous oxide emissions from agricultural soils can be classified into direct and indirect emissions. Direct emissions are those from applied nitrogen inputs including fertilizer, manure and biosolids. Indirect emissions are those associated with nitrogen loses via volatilization, run-off and leaching (Environment and Climate Change Canada, 2018). In Canada's National GHG Inventory Report, the IPCC accounting system is utilized and therefore this GHG accounting system was chosen for this thesis. However, the use of the IPCC accounting system is not without limitations which have been explored in previous literature, particularly in the case of biofuels. Searchinger et al., (2009) outlines crucial climate accounting errors in the IPCC method, where in the case of biofuels two main areas of emissions are not accounted for: 1) CO_2 emitted from tailpipes and smokestacks when bioenergy is being used 2) Changes in emissions from land used when biomass for energy is harvested or grown (Searchinger, et al., 2009).

The IPCC provides a tiered methodology that approximates direct emissions from agricultural soils as a fraction of soil nitrogen inputs expressed as an emission factor (EF). Tier I is the simplified accounting method and is the default approach for countries with limited information on nitrous oxide emissions (IPCC, 2006). The 2006 IPCC guidelines provide the default EF of 0.01 N_2O-N $kg^{-1}N$ which was derived from a global dataset of 800 observations (Bouwman, Boumans, & Batjes, 2002; IPCC, 2006). Where experimental data is available, the IPCC recommended approach is the Tier II methodology which utilizes country-specific emissions factors (IPCC, 2006). However, one criticism of using a country-specific EF to estimate emissions from nitrogen inputs is that other factors that potentially impact emissions are not factored in (Rochette, et al., 2018). Despite the limitations of the IPCC's Tier II methodology, this GHG accounting system will be utilized for the purposes of this thesis as it is the system used in Canada's own National GHG Inventory Report.

3.4.2 Canadian Direct Emission Factor Estimates

Rochette et al. proposed a Tier II methodology to account for direct nitrous oxide emissions from agricultural soils that are specific to Canadian conditions. This study utilized an empirical approach based on experimental data from 1990-2005 and proposed emissions factors at the ecodistrict level which are areas of size less than 100kha which are characterized by distinct biophysical and climatic conditions. This study found nitrous oxide emissions from nitrogen fertilizer application was a function of tillage intensity, irrigation, soil texture, topography, and practice of summer fallow. Estimates of emissions factors by ecodistrict were estimated using linear relationships between N_2O emissions and ratios of growing season precipitation to potential evapotranspiration. However, the authors of this study acknowledged the regression fit for the prairie region of Canada needed improvement (Rochette, et al., 2008).

Rochette et al. recently improved upon their previous work by including an updated study with a larger experimental dataset over the years 1980-2013. This updated dataset increased the number of observations occurring in the prairie provinces. In this study, estimated emission factors were updated and the relationships between factors that explain nitrous oxide emissions were refined. Rochette et al. found that the most important factor effecting N_2O emissions from nitrogen fertilizer application in Canada was growing season precipitation (Rochette, et al., 2018). This can be explained as rainfall determines soil water content and soil water-filled pore space (WFSP) which have been shown in previous works to be an indication of soil redox potential or the conditions that result in transformations of mineral nitrogen in the soil to nitrous oxide (Linn & Doran, 1984; Rochette, et al., 2008).

Rochette et al. performed a stepwise regression analysis including ratio of growing season precipitation to evapotranspiration, mean annual air temperature, crop type (perennial or annual), soil pH, texture, and organic carbon content. When including two of the five variables, Rochette et al., (2018) found that EFs could be predicted (R^2 from 0.68 to 0.85). From a simple empirical model of growing season precipitation, sand content and crop type, Rochette et al. (2018) found N_2O EFs could be accurately predicted. In this empirical model, growing season precipitation and sand are likely working as proxies for soil aeration conditions. However, for the prairie region there was found to be no difference in N_2O EF between soil textural classes. One potential explanation for this may be that the drier climate of the Canadian prairies results in lower emissions factors in all soils. Another potential explanation is the lack of studies on fine textured soils on the prairies in the dataset (Rochette, et al., 2018). Regardless, based on these findings, it appears the EF for the prairie region of Canada can be estimated based on the crop type.

In Rochette et al. (2018) the estimated Canadian national mean EF for annual crops when only synthetic N sources are included was 0.0065 ± 0.0039 kg N_2O-N $kg^{-1}N$. However, large deviations from the national mean are observed at the regional scale. For the prairie region the mean EF for organic and synthetic N inputs was estimated to be 0.0019 ± 0.00064 kg N_2O-N $kg^{-1}N$ with values ranging from 0-0.2 kg N_2O $kg^{-1}N$. The variations in mean EF across ecoregions indicates the limitations of using a national estimate for EF where it may vary significantly across ecoregions (Rochette, et al., 2018). The estimated emission factors from synthetic fertilizer applied by ecoregion are shown in Table 3-1. The reason for the difference between the 2008 and 2018 estimates is the differing methodological approach and differing datasets. In the 2008 study, the prairie region estimates were obtained from poorly fitted regression of N_2O emissions versus synthetic N rate, rather than from individual EFs as in the 2018 study. Additionally, the data set used in the more recent study had a larger data set pertaining to the prairie provinces (Rochette, et al., 2018; Rochette, et al., 2008). Therefore, the ecoregion EFs used in this thesis were those from the updated 2018 study.

Table 3-1 Estimated EF of synthetic fertilizer applied for ecoregions of Canada.

Ecoregion	**Soil N_2O EF kg N_2O-N kg^{-1}N**	**Source**
Eastern	0.012	(Rochette, et al., 2008)
	0.0211	(Rochette, et al., 2018)
Black soil zone	0.008	(Rochette, et al., 2008)
	0.0033	(Rochette, et al., 2018)
Brown & Dark brown soil zone	0.0016	(Rochette, et al., 2008)
	0.0016	(Rochette, et al., 2018)

3.4.3 Other GHG Emissions

For the purposes of this thesis, the direct N_2O emissions associated with nitrogen application were the only emissions considered. However, this is not a full accounting of the GHG emissions associated with nitrogen application, as indirect emissions including leaching, volatilization and run-off from nitrogen application were not considered. The full carbon footprint of nitrogen fertilizer is not captured in this study, as this study used only direct N_2O emissions which excludes other GHG emissions such as indirect emissions and those associated with the production and transport of nitrogen fertilizer.

3.4.4 Direct EF Conversions

The direct emissions from synthetic nitrogen fertilizer applied can be calculated from the emissions factor by a coefficient converting N_2O-N to N_2O, as shown in equation 3-12.

3-12

$$N_2O_E = EF_{Base} \times \frac{44}{28}$$

Where N_2O_E are emissions from inorganic nitrogen fertilizer applied (kg N_2O kg^{-1} N), EF_{Base} is the emissions factor (kg N_2O-N kg^{-1} N) and $\frac{44}{28}$ is a coefficient converting N_2O-N to N_2O (Environment and Climate Change Canada, 2018). Nitrous oxide emissions are then converted to carbon dioxide equivalent as shown in equation 3-13 (IPCC, 2012).

3-13

$$CO_2eq = N_2O_E \times 298$$

where N_2O_E are emissions from inorganic N fertilizer (kg N_2O /kg N), 298 is a conversion factor. The conversion factor of 298 is used to account for N_2O having 298 times the warming power of CO_2eq (Environment and Climate Change Canada, 2018). CO_2eq are the carbon dioxide equivalent emissions from inorganic nitrogen fertilizer (kg CO_2eq /kg N applied). Equation 3-13 is applied to the ecoregion EFs reported in literature to convert to kg C02eq kg$^{\mathbf{-1}}$ of applied N as shown in Table 3-2.

Table 3-2 Conversion of ecoregion EFs reported in literature to kg C02eq kg^{-1} N.

Ecoregion	**EF** (kg N_2O-N kg^{-1}N)	**Conversion** (kg C02eq kg^{-1} N)
Black soil zone	0.0033	1.545
Brown & Dark brown soil zone	0.0016	0.749

Source: (Rochette et al., 2018)

3.4.5 Theory for GHG Mitigation Cost

The GHG mitigation cost associated with reducing nitrogen fertilizer application rates is estimated in this thesis. The GHG mitigation cost is a function of the change in GHG emissions and net return. Net return (*NR)* was calculated as shown in equation 3-14, where the rate of nitrogen fertilizer (*N)* was the only production factor that was adjusted effecting yield. Net return

(\$ ha^{-1}) was calculated as the difference between the revenue of crop sales and the cost of nitrogen fertilizer applied (\$ ha^{-1}). Revenue of crop sales is price of canola (P_c) multiplied by yield (Y). Cost of nitrogen fertilizer applied is price of nitrogen fertilizer (P_N) multiplied by rate of nitrogen applied (N) (Karatay & Meyer-Aurich, 2018).

3-14

$$NR = P_C Y - P_N N$$

The GHG mitigation cost function is shown in equation 3-15. The GHG mitigation cost is calculated as the change in net revenue over the change in GHG emissions when comparing the economic optimal nitrogen rate to a reduced nitrogen rate. The net revenue at the calculated private economic optimum is denoted as NR_O, while the net revenue at a reduced nitrogen fertilizer rate is denoted as NR_R. The greenhouse gas emissions in CO_2eq at the economic optimal N rate scenario is denoted by GHG_O while GHG_R is the greenhouse gas emissions in CO_2eq in the reduced N rate scenario (Karatay and Meyer-Aurich, 2018).

3-15

$$GHG\ Mitigation\ Cost = \frac{NR_O - NR_R}{GHG_O - GHG_R}$$

3.4.6 Social Cost of Carbon

The N_2O tax rate was applied based on an estimated social cost of carbon for the direct emissions from nitrogen fertilizer application. To estimate the social cost of carbon associated with direct emissions from nitrogen fertilizer application, the calculated CO_2eq emissions in Table 3-2 were used along with the Government of Canada's current and scheduled carbon prices. As of April 2022, the price of carbon is currently at \$50 t^{-1} CO_2eq. The target price of carbon for 2030 is \$170 t^{-1} CO_2eq respectively (Government of Canada, 2022). In Table 3-3, the calculated tax on nitrogen (\$ t^{-1} N) is based on two social costs of carbon: \$50 t^{-1} CO_2eq (the 2022 price of carbon emissions in Canada) and \$170 t^{-1} CO_2eq (the scheduled price of carbon emissions for 2030) (Government of Canada, 2022). The EF factors specific to the black and brown soil zone ecoregions of Saskatchewan are utilized (Rochette et al. 2018). The N_2O tax rate was applied to the average 2019 price of urea, based on the guaranteed analysis of 46% nitrogen.

Table 3-3 Calculated tax on nitrogen based on two different carbon prices and two different EF factors specific to ecoregions of Saskatchewan.

Ecoregion	**EF^1**	**\$50 t^{-1} CO_2eq Tax on Nitrogen^2 (\$/tonne N)**	**\$170 t^{-1} CO_2eq Tax on Nitrogen^2 (\$/tonne N)**
Black	0.0033	77.27	262.71
Brown	0.0016	37.46	127.37

Sources: ^{1} (Rochette, et al., 2018) ^{2} (Government of Canada, 2022)

3.4.7 Economic Optimal Nitrogen Rate Post-Tax

The policy simulations conducted are in the short run where producers cannot change fixed factors to mitigate the increase in cost of nitrogen. The economic optimal nitrogen rate post nitrous oxide tax on nitrogen fertilizer can be estimated by modifying equation 3-5 which shows the optimal condition for a variable input equation. Where the nitrous oxide Tax is an added cost, as shown in equation 3-16.

3-16

$$f'_{V_{itN}}\left(v_{itN} | v_{it\ j\neq N}, x_{it}, z_{it}, \mu_{it}\right) = \frac{w_{itN} + Tax}{p_{it}}$$

3.4.8 Net Return Post-Tax

The net return following a nitrous oxide tax on nitrogen fertilizer can be estimated by modifying equation 3-14. The calculation of net return post tax is shown in equation 3-17. The net return post tax ($NR_{PostTax}$) is equal to the revenue of crop sales less the cost of nitrogen fertilizer applied less the cost of the tax. The cost of the tax is equal to the (Tax) multiplied by the quantity of nitrogen fertilizer applied (N) .

3-17

$$NR_{PostTax} = P_C Y - P_N N - Tax_N$$

3.4.9 Reduction in GHG Emissions Post-Tax

The reduction in GHG emissions from a N_2O tax relative to the privately optimal nitrogen rate was calculated as shown in equation 3-18. Where the reduction in GHG emissions GHG_R is equal to the amount of nitrogen fertilizer application reduced ($\triangle N$)multiplied by the associated GHG emissions (CO_2eq_N).

3-18

$$GHG_R = \triangle N \quad * CO_2eq_N$$

3.5 Summary

The theory of optimal nitrogen use, production function estimation, N_2O emission estimates, GHG mitigation cost and N_2O tax calculations was provided in this chapter. The optimal condition for nitrogen is derived from the canola production function and the first order condition of the profit maximization equation. The functional form of the production function was discussed, as well as the econometric methods and identification assumptions. The theory for estimating N_2O emissions associated with nitrogen application was based on the IPCC accounting system used by the Government of Canada in assessing its climate commitments under the Paris Climate Accord. The equations used to calculate the average GHG mitigation Cost were described. Finally, the calculations used in the policy scenario with a N_2O tax were outlined. The Government of Canada's own carbon pricing schedule were used to derive the social cost of carbon. The calculations for the post-tax optimal nitrogen rate, net revenue, and GHG emissions were described. Now that the conceptual framework is outlined, the next chapter will describe the data used.

CHAPTER 4 DATA

4.1 Introduction

The previous chapters have introduced the thesis topic and objectives, provided a review of relevant literature, and outlined the conceptual framework. This chapter describes the data used to obtain the results reported in The Estimation Process, Regression Results & Optimal N Use Estimates and Environmental Policy Scenario Results. This chapter includes a description of the data sources, representative nature of the data and the variables included in the canola production function model.

4.2 Data Sources

This section includes an explanation of the management, precipitation, and variety herbicide system data used for analysis. The management data used in this thesis is a very large and rich data set that was provided by Saskatchewan Crop Insurance Corporation (SCIC). SCIC generously provided producer reported management information that was collected through the administration of the provincial crop insurance program over the years 2011-2019. A data sharing agreement between the thesis author and the University of Saskatchewan was signed pertaining to confidentiality and information management. The precipitation, variety herbicide system and price data used from other sources were used to complement the existing SCIC management data set.

4.2.1 Management Data Source

The management data provided by SCIC is annually reported producer management information. Random audits of SCIC customers are completed to ensure validity of reported insurance information. As such, it is hoped that producers are incentivized to report information accurately. The data sample was selected for canola fields over the years 2011 – 2019 and for producers enrolled in the Saskatchewan Management Plus Program (SMP). Producers enrolled in the SMP program supply crop yields by legal land description on their production declaration form and provide additional production information such as variety and crop protection products used. There is no cost to this program and producers enrolled in crop insurance who report their production by legal land description on their production declaration form are automatically enrolled in SMP. The benefit of enrolling in the SMP program is an individual summary of management information mailed out to the producer. This data can help producers plan crop rotations, budgets and compare crop performance (Saskatchewan Crop Insurance Corporation, 2022). Variables in this management data set include an anonymous customer ID, yield, applied fertilizer rates, seeding date, crop, variety, grain risk zone, Rural Municipality, quarter section and year.

4.2.2 Precipitation Data Source

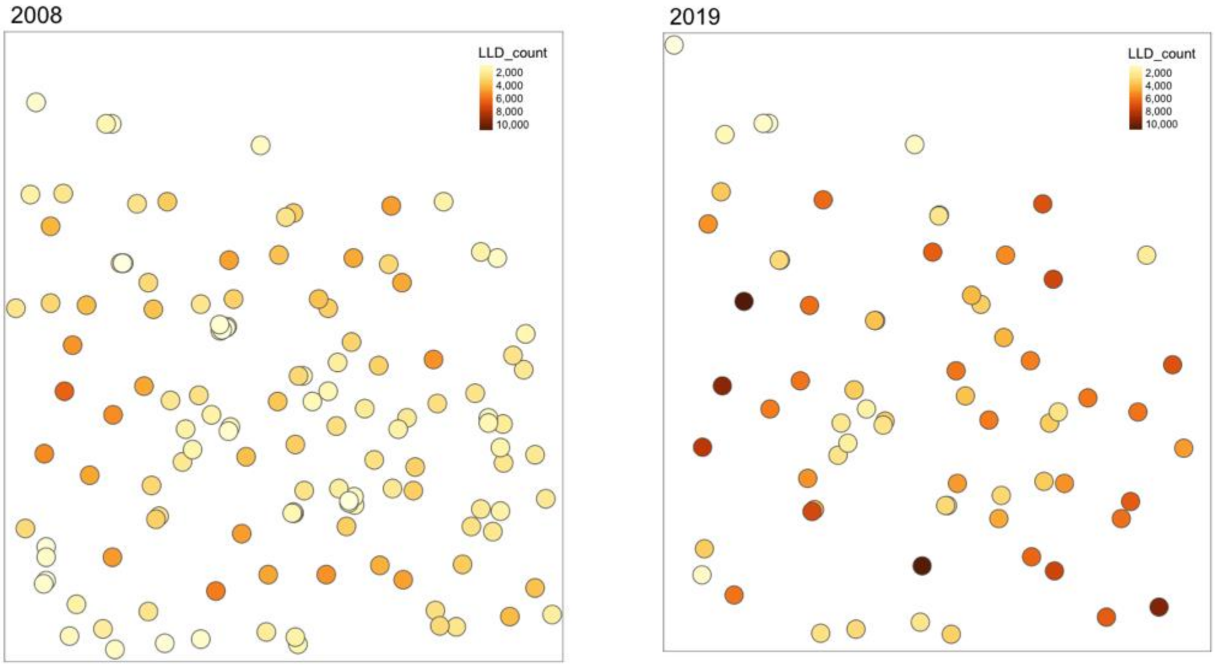
Monthly growing season precipitation data over the years 2008-2019 was sourced from Environment Canada's weather stations. From 2008-2019 there were an average of 113 weather stations in each year. The majority of fields in the data set were within a 25km buffer to the nearest weather station. However, the number of weather stations have been decreasing over time, which is depicted in Table 4-1 and Figure 4 (Environment and Climate Change Canada, 2019).

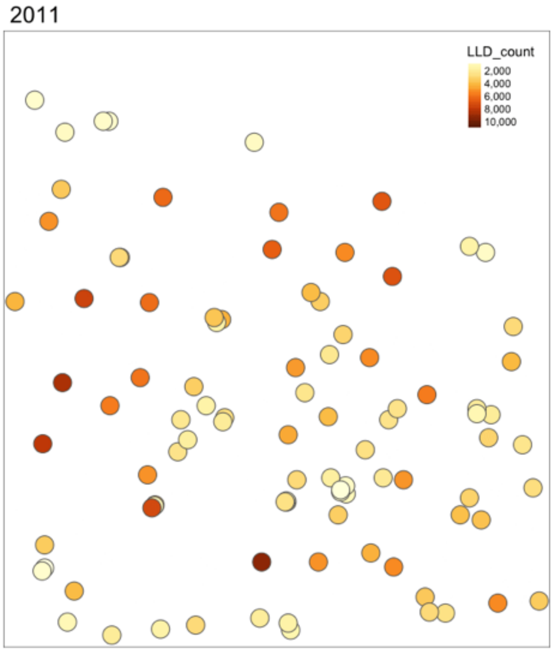
Table 4-1 Number of Environment Canada's weather stations by year.

Year	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
# of Stations	149	122	119	120	118	117	110	107	106	102	95	89

Source: (Environment and Climate Change Canada, 2019)

Figure 4-1 Weather stations in 2008, 2011, and 2019 and number of Saskatchewan LLD's associated with them.





Source: (Environment and Climate Change Canada, 2019)

4.2.3 Variety Herbicide System Data Source

The herbicide system attributed to each canola variety grown was sourced from the Government of Canada's online database of registered crop varieties. The varieties were categorized into herbicide system groups: Clearfield (imidazolinone resistant), Liberty Link (glufosinate resistant) and Roundup Ready (glyphosate resistant). This classification was based on the transgene recorded for each variety in the Government of Canada's variety registration records (Government of Canada, 2021).

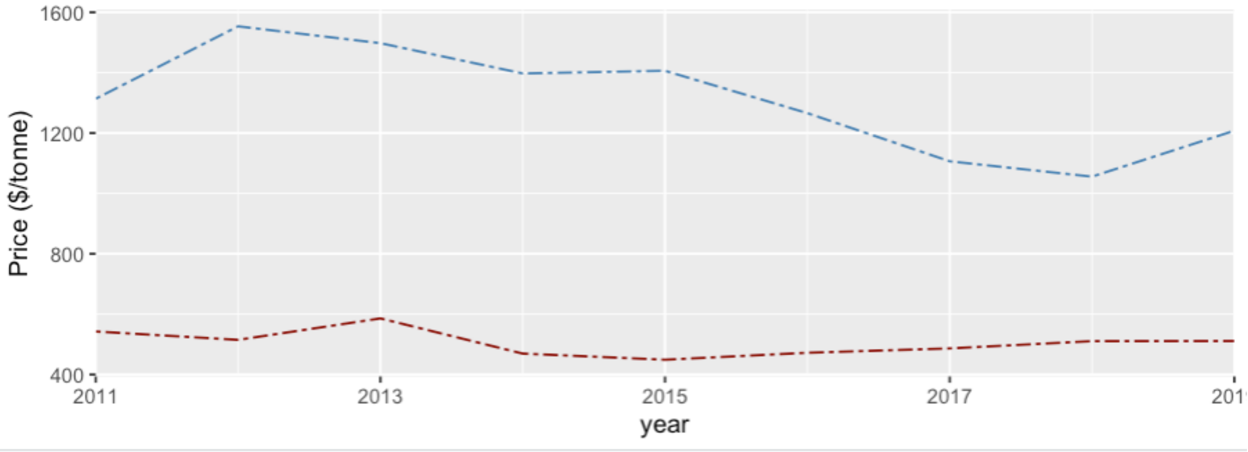
4.2.4 Price Data

The producer survey data used from SCIC did not include individual producer nitrogen fertilizer costs or expected canola price. In order to gauge historical nitrogen to canola price ratios over the years 2011-2019, other sources were used. Both canola prices and fertilizer prices used were adjusted for inflation to 2019 prices using the consumer price index (CPI) from Statistics Canada (Statisitcs Canada, 2019). The historical prices for dry urea (46-0-0) were taken from the Alberta Agriculture and Forestry which conducts a yearly farm input survey (Alberta Agriculure and Forestry, 2019). The average dry urea price for a growing season was calculated as the average price over the months October – December of the previous year and January – March of the current year. This was based on the assumption that most producers make their fertilizer decisions and purchases during the late fall, winter and spring leading up to a growing season. The input price of nitrogen derived by converting the price of urea to the price for pure nitrogen based on the guaranteed analysis of dry urea of 46% nitrogen. The price of pure nitrogen from 2011-2019 is shown in Figure 4-2 Panel A as the blue dashed line. The expected prices for canola were taken from the Saskatchewan Crop Planning Guide which publishes an expected farmgate price in the winter leading up to each growing season (Saskatchewan Ministry of Agriculture, 2022). The annual expected canola prices are shown in Figure 4-2 Panel A as the red dashed line. Expected canola prices over 2011 - 2019 ranged from a high in 2013 of \$529 tonne^{-1} to a low of \$418 tonne^{-1} in 2015. Relative to the expected price of canola, there have historically been larger fluctuations in the price of nitrogen fertilizer when averaged over the months of October – March. Over the years 2011-2019, the highest nitrogen price was in 2012 at \$1390 tonne^{-1} while the lowest nitrogen price was in 2018 at \$1035 tonne^{-1}. The historical annual data used for nitrogen prices and expected canola prices are used to calculate an annual nitrogen to canola price ratio which is shown in Figure 4-2 Panel B. The highest cost ratio using this price data set occurs in 2015 with a cost ratio of 3.13 while 2018 has the lowest cost ratio of 2.07.

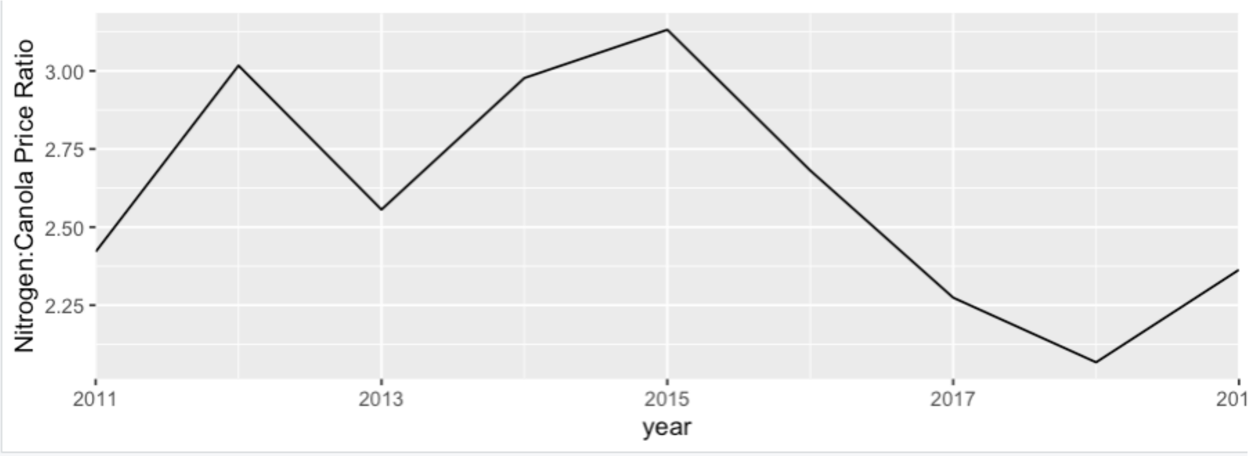
Figure 4-2 Historical Annual Price Data for Nitrogen and Canola.

In Panel A the blue dashed lines indicate the price of pure nitrogen[1] while the red dashed line indicates the expected price of canola[2]. Prices are in 2019 real prices. Panel B represents the cost ratio of nitrogen to expected canola prices.

Panel A



Panel B



[1] Source: (Alberta Agriculure and Forestry, 2019) [2] Source:(Saskatchewan Ministry of Agriculture, 2022)

4.3 Representative Nature of Management Data

This section aims to provide insight on the representativeness of the data from the SMP Program. Table 4-2 and Table 4-3 compare the Statistics Canada Census of Agriculture Crop provincial reported canola area seeded and yield to that of the SCIC Enrollment data and the SMP Program data (Statisitics Canada, 2022).

Table 4-2 Canola seeded area and yield are reported by provincial records, SCIC data, SMP program data and the selected SMP sample data.

Year	Provincial Reported Data[1]	SCIC Data[2]	SMP Program Data[2]	Selected SMP Sample
		Canola Seeded Area (ha)		
2011	4,006,475	2,844,516	1,524,144	270,179
2019	4,765,277	3,467,296	1,970,269	269,324
2011-2019	36,576,285	28,477,849	14,876,966	2,597,590
		Canola Mean Yield (kg/ha)		
2011	1800	1912	2061	2167
2019	2396	2459	2566	2686
2011-2019	2053	2125	2282	2371

1 Source: (Statistics Canada, 2019) 2 Source: (Saskatchewan Crop Insurance Corporation, 2019)

Table 4-3 Canola seeded area and yield of SCIC Enrollment, SMP program and selected SMP sample as reported as percentages relative to the provincial reported data.

Year	% SCIC Prov. Reported[1]	% SMP of Prov. Reported[1]	% Selected Sample of Prov. Reported[2]
		Canola Seeded Area (ha)	
2011	71%	38%	7%
2019	73%	41%	6%
2011-2019	78%	41%	7%
		Canola Mean Yield (kg/ha)	
2011	106%	114%	120%
2019	103%	107%	112%
2011-2019	104%	111%	115%

1 Source: (Statistics Canada, 2019) 2 Source: (Saskatchewan Crop Insurance Corporation, 2019)

This section includes a discussion of the representativeness of the SMP data for canola area seeded and yield followed by an overview of the potential selection bias. This section is concluded by a description of the data filtering process used to select the data sample used in analysis.

4.3.1 Canola Area Seeded and Yield Representativeness

Based on the provincial reported canola area seeded (Statisitics Canada, 2022), over the years 2011-2019 78% of canola hectares seeded were insured by Saskatchewan Crop Insurance Corporation. From 2011-2019, 52% of canola hectares seeded insured by SCIC were enrolled in the SMP program. From 2011-2019, 41% of provincial reported canola area seeded were enrolled in the SMP program. From 2011-2019, 7% of provincial reported canola area seeded were in our selected sample used for the estimation of the canola production function. Over the years 2011-2019, canola insured by Saskatchewan Crop Insurance Corporation was 104% of the provincial reported mean canola yield (Statisitics Canada, 2022). From 2011-2019, canola hectares enrolled in SMP yielded 111% of the provincial reported mean canola yield. From 2011-2019, the mean yield of our selected sample was 115% of the provincial reported mean canola yield.

4.3.2 Selection Bias

In comparing the selected sample to the reported provincial seeded area of canola, our selected sample size is large representing approximately 7% of seeded canola hectares over the years 2011-2019 in Saskatchewan. However, when comparing the selected sample to the reported provincial average canola yield, it appears that our selected sample is upwardly biased in terms of canola yields. This has implications for econometric results made from this selected sample, as the producers enrolled in Saskatchewan Crop Insurance and the SMP program are potentially producers who on average are higher producing. Therefore, extrapolating the canola yield and nitrogen use estimates derived from this selected sample to all of Saskatchewan may result in an upward biased. This is perhaps unsurprising, as those producers who take the time to provide additional management information detailed down to the specific land location may be hypothesized to be the higher-end managers of Saskatchewan producers. An alternative to producer reported canola field data, is experimental field trials. However, the results from experimental canola field trials have their own challenges as researchers produce results under the select conditions that occur within the research trials. There are a complex set of factors that affect canola productivity, and a systems approach with multiple factors is ideal to explore the yield potential of canola. However, the cost and time required to perform factorial experiments over multiple years and locations in order to represent the wide variety of conditions and farms that exist in Saskatchewan would be very costly (Liu, Gan, & Poppy, 2014). There is potential for selection bias in using the SMP producer reported data to estimate the canola production function and the optimal nitrogen application rate. However, due to the large sample size of producers over a wide range of time, geography, management and climatic factors, this data is perceived as being able to provide valuable insight on the canola production function in Saskatchewan.

4.3.3 Selected Sample

The data used in analysis was selected by removing observations with missing information and filtering entries with extreme observations. Of the original SMP program data set of canola grown over the years 2011-2019, entries of irrigated canola fields were removed to select for dryland canola production only. Observations that were entered multiple times were also removed from the data set. Any entries with missing information that was required for analysis such as incomplete records of applied fertilizer rates, previous crop type, reported yield, seeding date and variety records were removed from the sample used in analysis.

The data was filtered as shown in Table 4-4. Applied nitrogen, phosphorous, sulphur, and potassium rates were filtered to remove extreme observations based on an understanding of reasonable values in the Saskatchewan context. Field size was filtered to a minimum of 32 hectares, with the goal of eliminating residential or acreage fields. Fields that were insured by SCIC by a producer in Saskatchewan but were located in the province of Alberta were also removed from the sample. Observations in risk zones with a low number of observations over the years 2011-2019 (n<40) were removed for producer confidentiality reasons. The data used in analysis was selected for Argentine variety canola (*B. napus*), while those classified as polish varieties (*B. rapa*) and juncea (*B. juncea*) were removed. Data was filtered for varieties that are classified as Liberty Link, Roundup Ready and Clearfield herbicide tolerant.

Table 4-4 Description of the data filtering of the SMP SCIC raw data.

Variable Filtered	**Allowable Range**	**Observations Removed**	**Sample N**
			55,968
Hectares	≥ 32	6,905	49,063
Nitrogen	>40	641	48,422
LLD located in Alb.		638	47,784
Risk Zone	RZ 3, 4 and 13 removed (n<40)	54	47,730
Phosphorous	≤ 90	11	47,719
Potassium	≤ 60	59	47,660
Sulphur	≤75	70	47,590
Seeding date	04/24 ≥ x ≤06/10	465	47,125
Variety	*B. napus*	12	47,113
Variety herb system	CL, RR, LL herbicide tolerance	54	47,059
Total		8,909	47,059

4.4 Description of Model Variables

This section includes an overview of the variables included in the model, followed by the means of each variable within the filtered data by year and risk zone. A list of the variables included in the canola production model and a brief description of the variables is shown in Table 4-5.

Table 4-5 Description of variables included in the production function.

	Variable	**Description**
Continuous	Yield[1]	Average canola yield reported for field (kg ha^{-1})
	Nitrogen[1]	Applied actual nitrogen (kg ha^{-1})
	Phosphorous[1]	Applied actual phosphorous (kg ha^{-1})
	Potassium[1]	Applied actual potassium (kg ha^{-1})
	Sulphur[1]	Applied actual sulphur (kg ha^{-1})
	Seeding date[1]	Seeding date in number of days after May 14
	Avg Precipitation[2]	Average rainfall for growing season (May – August) of the past 3 years as recorded by the nearest available weather station (mm)
	Variety index[1]	Variety grown yield % of the check variety (L252) on average. 201 different varieties
Dummy	Pulse previous crop[1]	Dummy variable for pulse previous crop (=1). Pulses are classified as nitrogen fixing crop and in the sample this includes field peas, fababeans and lentils
	Cereal previous crop[1]	Dummy variable for cereal previous crop (=1). Cereals in the sample include wheat (HRSW, HWS, Winter), durum, barley, and oats.
	Oilseed previous crop[1]	Dummy variable for oilseed previous crop (=1). Oilseeds are classified as flax and canola or rapeseed.
	Fungicide[1]	Dummy variable for fungicide (=1) application
	Roundup Ready[3]	Dummy variable for Roundup Ready (=1) variety herbicide system
	Liberty Link[3]	Dummy variable for Liberty Link (=1) variety herbicide system
	Clearfield[3]	Dummy variable for Clearfield (=1) variety herbicide system
Categorical	SCIC Soil productivity rating[1]	Soil productivity class rating (14 categories) as classified by Saskatchewan Crop Insurance Corporation based on SAMA productivity classes. A = high productivity soil. P = low productivity soil.
	Producer[1]	Producer ID
	Year[1]	Year of observation
	Risk zone[1]	Grain risk zones of Saskatchewan as categorized by crop insurance.

[1] Source: (SCIC, 2019)

[2] Source: (Environment and Climate Change Canada, 2019)

[3] Source: (Government of Canada, 2021)

4.4.1 Yield

Yield is the dependent variable in the canola production function model. In this data set, canola yields are reported as the average canola yield in a specific year of a specific legal land location.

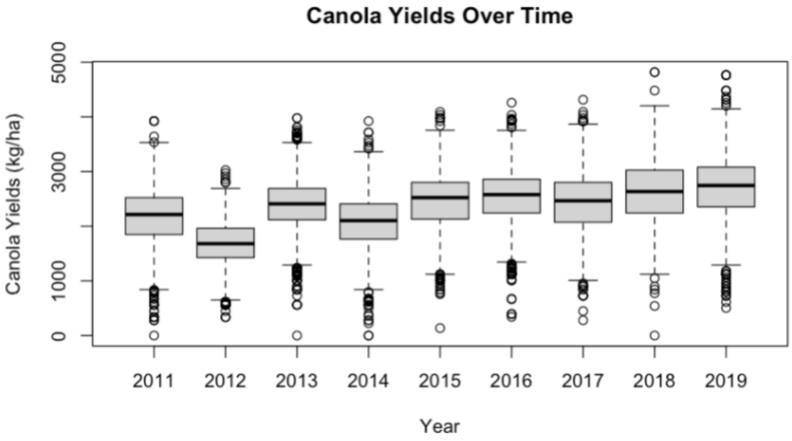
As shown in Table 4-6 the average canola yields observed in the sample have generally been increasing over time. Over 2011-2019, the highest average annual yield occurred in 2019 and the lowest average annual yield was observed in 2012. Average canola yields over 2011-2019 vary by the risk zones of Saskatchewan as shown in Figure 4-4. Average canola yields over the years 2011-2019 are lowest for the risk zones 2, 6 and 1 and highest for the risk zones 23, 14, 17 and 20.

Table 4-6 Average reported canola yield by year in dataset.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
Avg. Yield (kg ha^{-1})	2167	1685	2397	2087	2437	2587	2448	2636	2686

Source: (SCIC, 2019)

Figure 4-3 Canola yields over time in the sample (47,059)[1].



Source: (SCIC, 2019)

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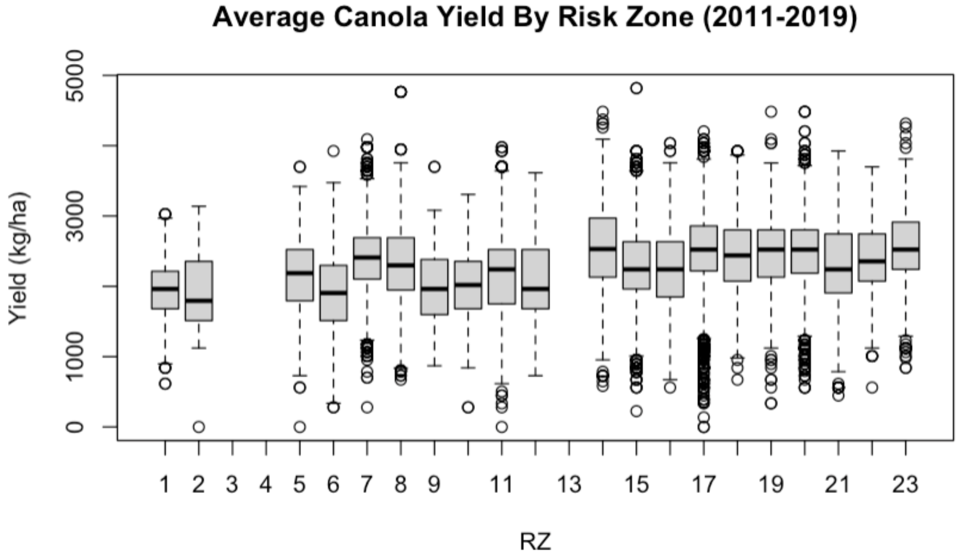
[1] *Note on interpreting box-plots: The thick black bar indicates the median. The lower and upper hinges of the gray box correspond to the first and third quartiles (the 25th and 75th percentiles). The distance between the first and third quartiles is known as the interquartile range(IQR) and equal to the gray box. The upper whisker extends from the hinge to the largest value no further than 1.5 * IQR from the hinge. The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge. Observations outside of the whiskers are outliers and are plotted individually. This is equal to roughly a 95% confidence interval for comparing medians* (Wickham, 2016).

Figure 4-4 Average canola yields over the years 2011-2019 by risk zone.



Source: (SCIC, 2019)

4.4.2 *Fertilizer*

This section describes the nitrogen, phosphorus, sulphur, and potassium application rates in the selected sample by year and by risk zone. This section also includes an important note on the distinction between applied vs. actual vs. absorbed nutrients.

4.4.2.1 *Applied vs. Available vs. Absorbed Nutrients*

The available dataset from SCIC provides data on *applied* nitrogen (N), phosphorous (P), potassium (K) and sulphur (S). Our data set lacks observation of soil *available* nutrients, which is a potential weakness of our analysis as soil nutrients that are available to the plant are what drives crop productivity. In acknowledging this discrepancy, the crop production model controls for other effects that have been shown in agronomic literature to effect soil fertility and available nutrients including soil productivity (available nutrients varying by different soil productivity classifications) and previous crop (controlling for nitrogen fixing crops grown the preceding year). There is also an important distinction between applied vs. absorbed nutrients. The actual *absorption* of nutrients by a crop in a given year depends on several factors such as the mobility of the nutrient and soil organic matter content (Bauer & Black, 1994). For example, nitrogen is a soil mobile nutrient and is generally used by the crop during the current growing season. In contrast phosphorous is less mobile in the soil and most crops only recover 10 to 30 percent of the phosphorous fertilizer in the first year after application (Government of Saskatchewan, 2021). Therefore, previous phosphorous reserves in the soil are crucial to crop absorption of phosphorous in a growing season. While this study focuses on the optimal nitrogen rate applied, the distinction between nutrient application, availability, and absorption is an important one in crop nutrient recommendations and decisions.

4.4.2.2 Nitrogen

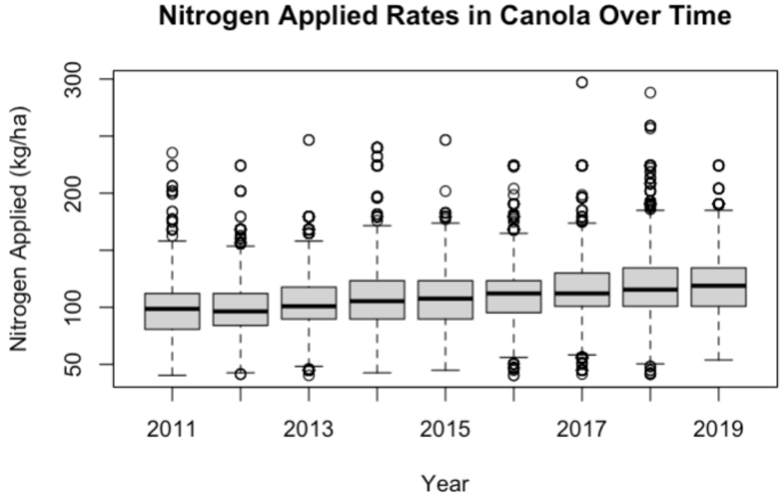
Nitrogen is one of the main determinants of canola yield. A strong yield response to nitrogen applied has been found for canola in Saskatchewan, as most soils on the prairie of Canada are deficient in plant available nitrogen (Grant & Bailey, 1993). The nitrogen information available in the SCIC data set is producer reported applied actual nitrogen each year on an individual field. The average nitrogen application rates over the years 2011-2019 have been trending upwards as shown in Table 4-7. In each year there was a wide range of producer reported nitrogen application rates in the data set as shown in Figure 4-5. The average nitrogen application rates vary by risk zone over the years 2011-2019 as shown in Table 4-7. The lowest average nitrogen application rates are observed in the risk zones 1, 6, 12 and 10 with the highest average applied nitrogen rates observed in risk zones 7, 14, 17 and 8.

Table 4-7 Average applied nitrogen rates (kg ha^{-1}) by year in the dataset.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
Avg. Applied N	97.7	98.7	103.2	106.1	107.8	110.6	115.0	118.2	120.5

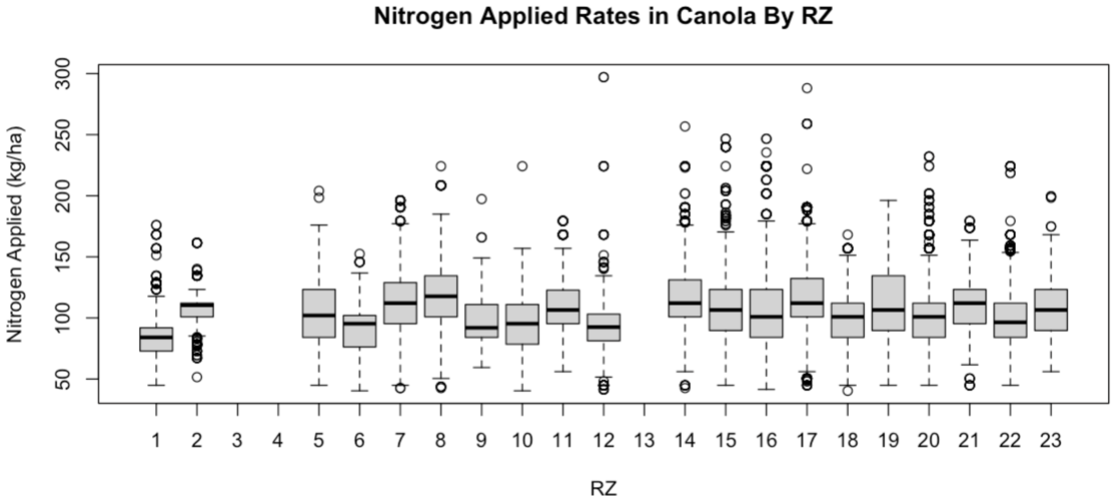
Source: (SCIC, 2019)

Figure 4-5 Nitrogen applied rates in Canola over time in dataset.



Source: (SCIC, 2019)

Figure 4-6 Nitrogen applied rates in Canola over time in dataset.



Source: (SCIC, 2019)

4.4.2.3 Phosphorous, Sulphur and Potassium

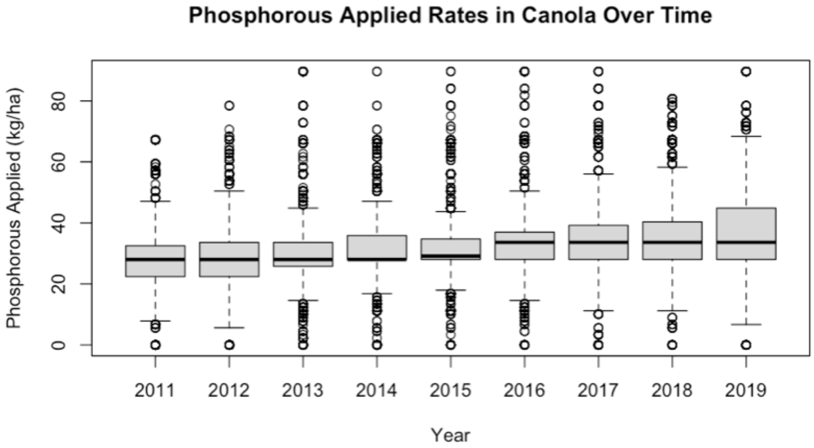
In addition to nitrogen, the nutrients phosphorous, sulphur and potassium are essential nutrients to canola production. Previous studies have found that a canola plant takes up 62–12–45–28 kg of N–P–K–S for t^{-1} yield (Assefa, et al., 2018). In the dataset used in this analysis, phosphorous, sulphur and potassium observations are reported in applied actual nutrients in a specific field in a given year. Over the years 2011-2019, applied nutrients all have been trending upwards as shown in Table 4-8 . In terms of quantity applied, phosphorous is the second highest quantity nutrient applied followed by sulphur while potassium is applied in the smallest quantity on average. The boxplot of applied phosphorous, sulphur and potassium rates annually is shown in Figure 4-7, Figure 4-8, and Figure 4-9. As shown in Table 4-9, the average application rates of phosphorous, sulphur and potassium also vary by Risk Zone.

Table 4-8 Average applied phosphorous, potassium and sulphur (kg ha^{-1}) over the years 2011-2019.

Year	**Average Applied P**	**Average Applied K**	**Average Applied S**
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
2011	27.7	3.2	19.0
2012	28.7	3.1	18.5
2013	30.1	3.6	19.1
2014	31.2	3.5	20.1
2015	31.4	3.8	21.0
2016	33.3	3.9	21.2
2017	34.3	5.2	22.4
2018	36.1	5.4	23.0
2019	37.2	6.4	22.6

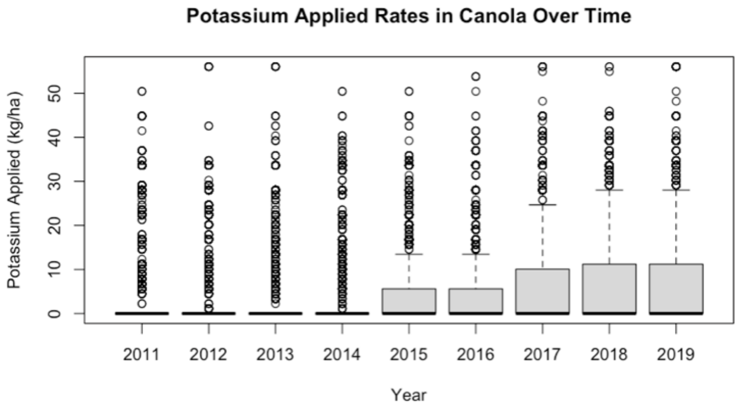
Source: (SCIC, 2019)

Figure 4-7 Phosphorous applied rates in Canola over time in dataset.



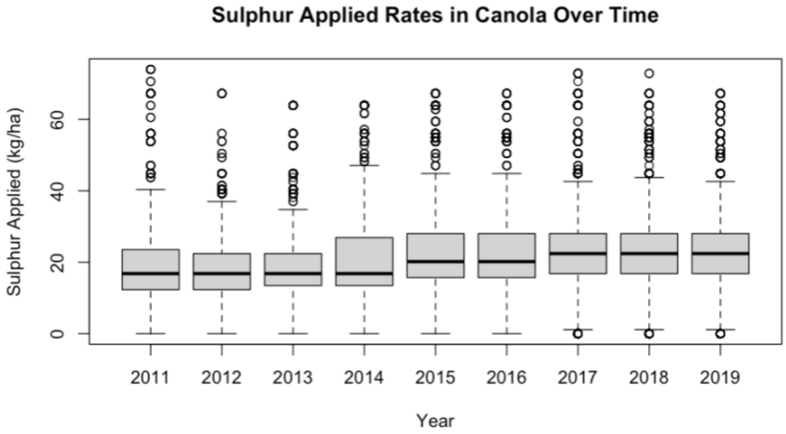
Source: (SCIC, 2019)

Figure 4-8 Potassium applied rates in Canola over time in dataset.



Source: (SCIC, 2019)

Figure 4-9 Sulphur applied rates in Canola over time in dataset.



Source: (SCIC, 2019)

Table 4-9 Average applied phosphorous, potassium and sulphur (kg ha^{-1}) for the years 2011-2019 by risk zone.

Risk Zone	**Average Applied P**	**Average Applied K**	**Average Applied S**
1	30.1	0.8	13.6
2	29.7	2.1	18.0
5	32.9	5.6	16.7
6	28.8	0.8	14.0
7	35.2	3.7	20.7
8	33.0	1.3	19.9
9	30.7	2.4	16.2
10	28.4	3.1	14.9

11	34.5	5.2	21.4
12	29.8	0.5	13.9
14	36.5	9.8	22.5
15	33.4	2.6	21.9
16	29.6	2.4	19.2
17	32.5	6.1	23.0
18	29.9	2.6	19.0
19	28.4	2.0	18.8
20	30.8	1.8	17.8
21	31.1	5.6	24.7
22	30.7	3.8	19.9
23	31.8	5.1	23.2

Source: (SCIC, 2019)

4.4.3 Seeding date

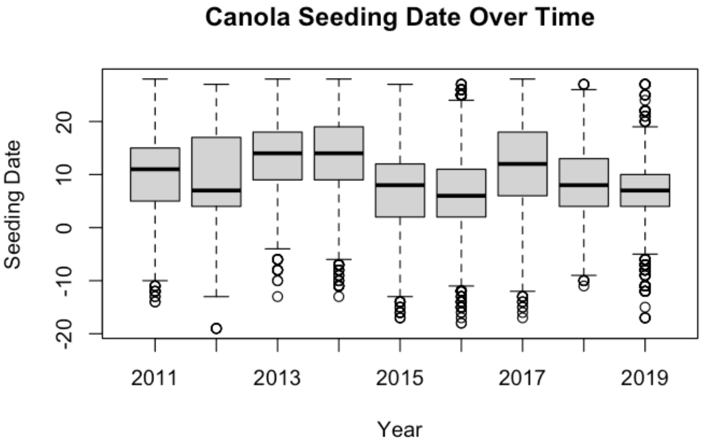
Studies have shown that the seeding date of canola is another important management factor of yield (Angadi, Cutforth, McConkey et al., 2004; McKenzie, Bremer, Middleton, et al., 2011; Pavlista, Isbell, Baltensperger, et al., 2011; Assefa, et al., 2018). As shown in Table 4-10 and Figure 4-10, average seeding date varies by year. Seeding date is impacted by a variety of environmental conditions that determine when producers plant canola. For example, in the years 2013 and 2014 the average seeding date for canola is later (14 days after May 14) when compared to other years in the sample. This is likely due to the wet conditions experienced across the majority of the province during these growing seasons which delayed seeding. The average seeding date of canola varies by risk zone as shown by Figure 4-11. This is likely due to different risk zones having different environmental conditions including soil moisture conditions and temperature which impact the time of canola seeding.

Table 4-10 Average Seeding date (in number of days after May 14) by year.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
Avg. Seeding Date	10	10	14	14	8	6	12	8	7

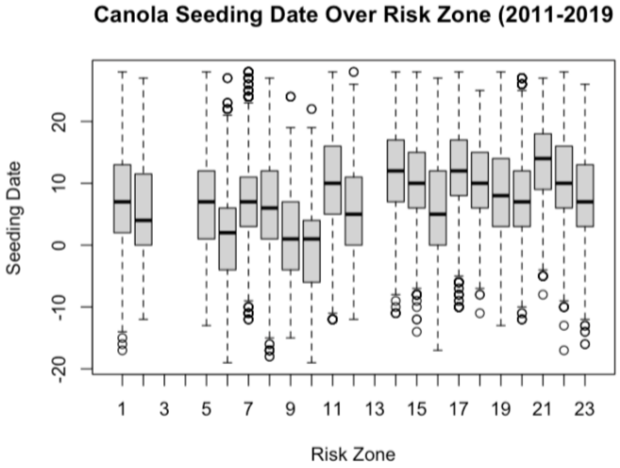
Source: (SCIC, 2019)

Figure 4-10 Average Seeding date (in number of days after May 14) by year.



Source: (SCIC, 2019)

Figure 4-11 Average Seeding date (in number of days after May 14) in the years 2011-2019 by risk zone.



Source: (SCIC, 2019)

4.4.4 Historical Growing Season Precipitation

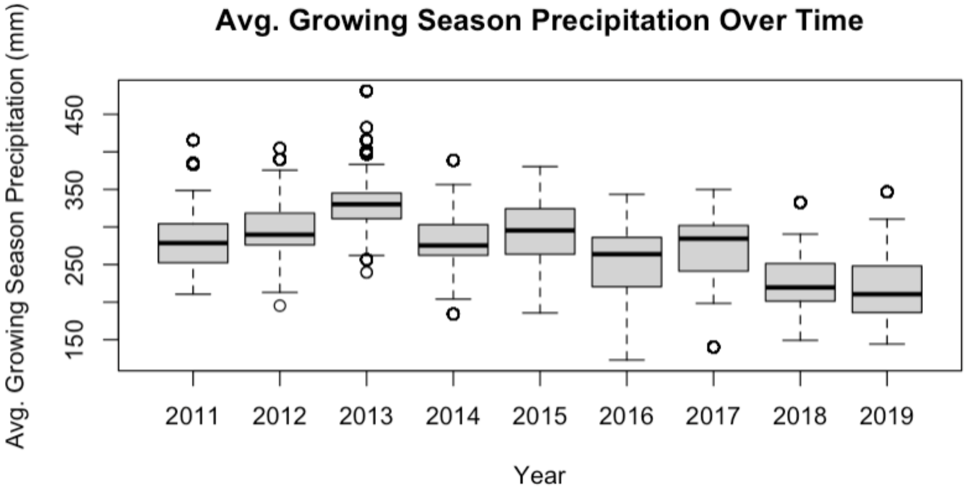
Previous literature has indicated that soil moisture is a very important factor in crop production (White, et al., 2020). The reserves of water in the soil greatly impact canola yields as research has shown an average yield gain of 7.2kg ha^{-1} for each millimeter of available water between 125 - 600mm (Assefa, et al., 2018). The arid conditions of the Canadian prairies often result in moisture being a limiting factor in dry land crop yields, and therefore the inclusion of a soil moisture data in the crop production function was considered important (White, et al., 2020).

However, there was limited available data of Saskatchewan soil moisture at a disaggregated level over the time period desired for this analysis. Therefore, historical average growing season precipitation was included in the model as a proxy for soil moisture. The average previous three years growing season precipitation (May – August) as recorded by the nearest available weather station is included in the model as a proxy for soil residual moisture. Over the years 2011-2019, the previous three-year average growing season precipitation varies greatly between years as shown in Table 4-11 and Figure 4-12. Over Saskatchewan as a whole, in 2013 the previous 3 years were the wettest on average while in 2019 the previous 3 years were the driest on average. Average historical 3-year precipitation also varies by risk zone as shown in Figure 4-13. The Risk Zones with the lowest 3-year historical precipitation on average over the years 2011-2019 were risk zones 10, 9 and 22. While the highest 3-year historical precipitation on average over the years 2011-2019 were risk zones 1, 11, and 14.

Table 4-11 Historical precipitation (mm) of previous 3 years over 2011-2019.

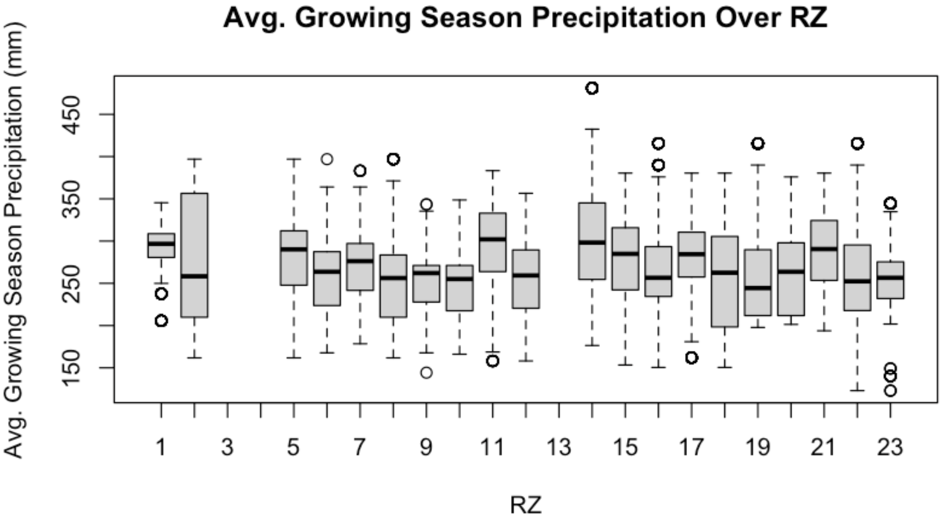
Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
3 Year Avg. Precip.	278	298	334	281	297	254	275	224	218

Figure 4-12 3 Year Average Growing Season Precipitation over the years 2011-2019.



Source: (SCIC, 2019)

Figure 4-13 3 Year Average Historical Growing Season Precipitation from 2011-2019 by Risk Zone.



Source: (SCIC, 2019)

4.4.5 Growing Season Precipitation

Canola yields are greatly impacted by environmental conditions, including growing season (May – August) precipitation. When aggregating performance trial data across North America, it has been found that proper quantities of precipitation and timing of available water is a large determinant of canola yield (Assefa, et al., 2018). Previous works have supported this finding that excessive or limited precipitation can reduce crop yields in the form of reduced growth, disease pressure and reducing plant available nutrients (Franklin, Kav, Nate, Yajima, & Reid, 2005; Bedard-Haughn, 2009). Therefore, the growing season precipitation (May – August) that was recorded at the nearest weather station (mm) was included in the model.

Over the years 2011-2019, the growing season precipitation varies between years as shown in Table 4-13 and Figure 4-14Figure 4-12. In the data set, the reported growing season precipitation was the lowest on average in 2017 while the lowest growing season precipitation was reported to have occurred in 2012. The growing season precipitation varies by risk zone as shown in Figure 4-15. The risk zones with the lowest growing season precipitation on average over the years 2011-2019 were risk zones 9, 10 and 18. While the risk zones with the highest growing season precipitation on average over the years 2011-2019 risk zones 21, 1, and 5.

Table 4-12 Growing season precipitation (mm) over 2011-2019.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
GS Precipitation	236	321	228	316	222	287	166	196	227

Figure 4-14 Growing Season Precipitation over the years 2011-2019.

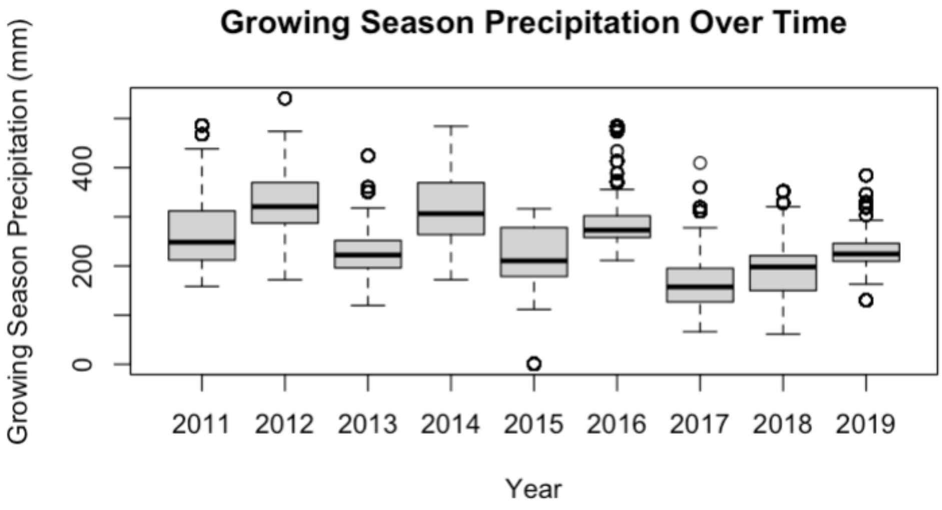
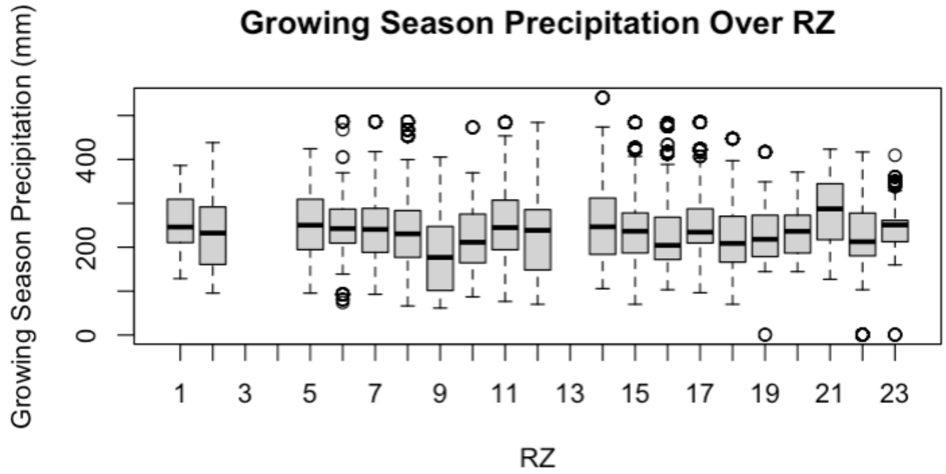


Figure 4-15 Growing Season Precipitation from 2011-2019 by Risk Zone.



4.4.6 Variety index

The variety index was calculated as:

4-1

$$Variety\ index_{k} = \frac{mean\ yield\ (variety_{k})}{mean\ yield\ (L252)} * 100$$

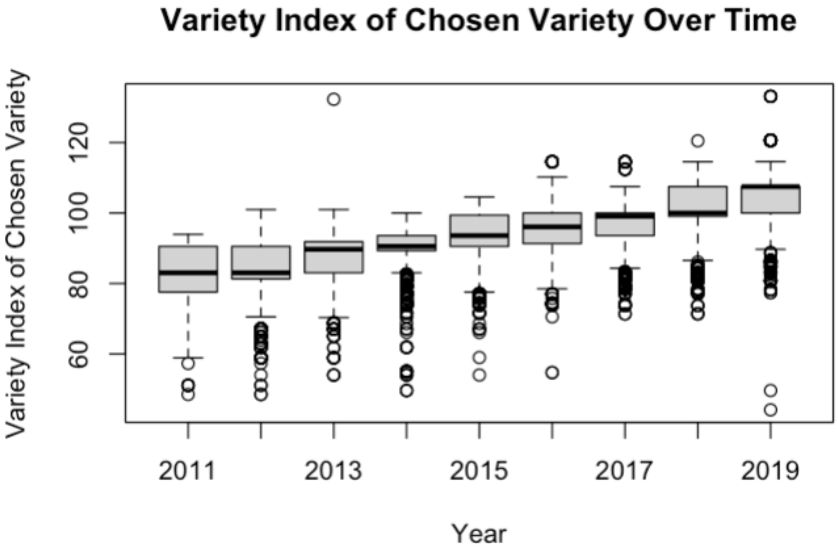
where a specific variety index is calculated for each specific canola variety (k) that is equal to the mean yield of the variety divided by the mean yield of the reference variety (L252). L252 was chosen as the reference variety for the data set based on the 2019 Saskatchewan Seed Guide which used L252 as the reference variety in the reporting of the canola performance trials (Government of Saskatchewan, 2019). Additionally, L252 is the most commonly grown canola variety in the data set accounting for 13% of the total observations. There were 215 different canola varieties in the dataset over the years 2011-2019. See Appendix A for a comprehensive list of the 215 canola varieties used in the analysis including the individual variety index, mean yield and variety age of each canola variety. Over the period 2011-2019, the average variety index of the chosen variety grown by producers is increasing as shown in Table 4-13 and Figure 4-16. In 2011 the average variety index relative to 252 was 84% while in 2019 it increased to 104%.

Table 4-13 Average variety index (mean yield % of variety relative to L252) over the years 2011-2019.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
Variety Index	83.5	84.3	87.1	90.1	93.2	95.6	97.6	101.6	103.9

Source: (SCIC, 2019)

Figure 4-16 Variety index (mean yield % of variety relative to L252) of chosen variety over 2011-2019.

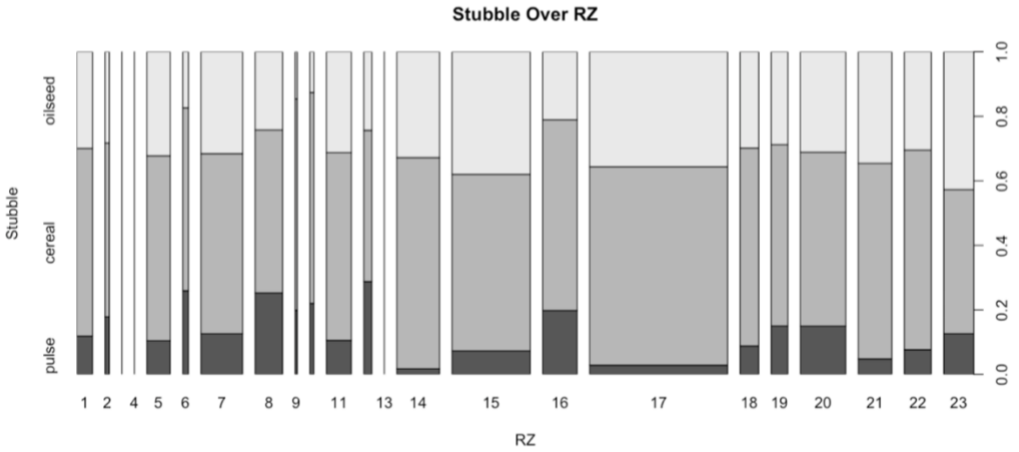


Source: (SCIC, 2019)

4.4.7 Previous crop

The previous crop rotation of a field has been found to impact canola yield, with nitrogen fixing legumes such as field peas and lentils having been found to boost canola yields compared to non-legumes such as cereals (O'Donovan, et al., 2014). The previous crop variable is classified as what crop was grown on a field in the previous year. The previous crop variable is categorized into three groups: pulse, cereal, and oilseed. Pulse crops are classified as nitrogen fixing crops and in the dataset, this includes field peas, fababeans and lentils. Cereal crops in the sample include wheat (HRSW, HWS, Winter), durum, barley, and oats. Oilseeds that are within the dataset are flax and canola. When looking at previous crop on average over both year and risk zone, the most prevalent previous crop category is cereal followed by oilseed, with pulse being the least prevalent in the dataset. The previous crop of the field sowed to canola also varies by risk zone, as shown in Figure 4-17 with some risk zones growing canola on a higher percentage of pulse ground relative to others on average over the years 2011-2019.

Figure 4-17 Previous crop observations over 2011-2019.

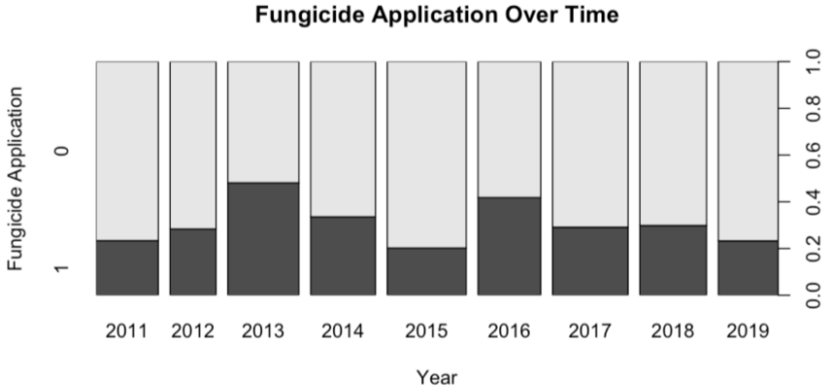


Source: (SCIC, 2019)

4.4.8 Fungicide

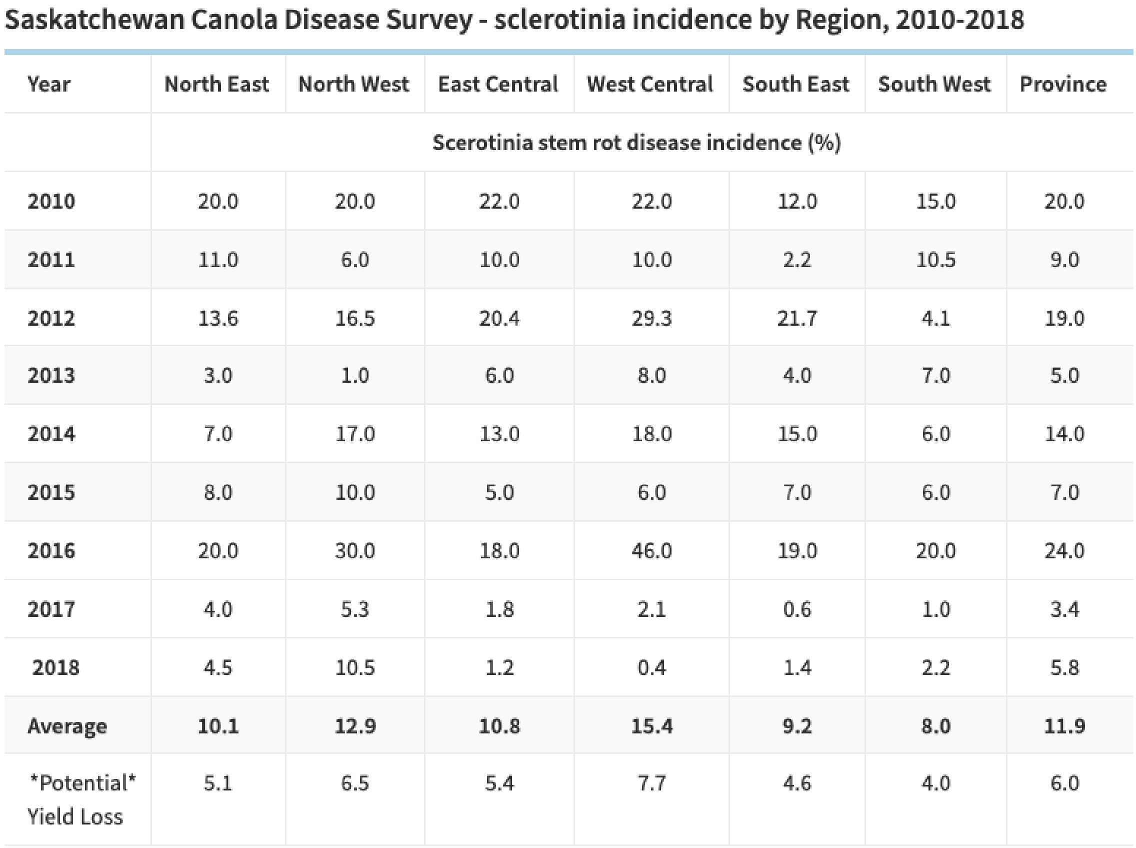
Fungicide is another factor that can have an impact on canola production, with previous research finding applications of fungicide can combat diseases that reduce canola yield. Previous studies have observed a significant yield benefit from fungicide application in canola when disease incidence is high (Kutcher and Wolf, 2006). The fungicide variable in the data set is a dummy variable for fungicide application [1,0]. The proportion of observations that received a fungicide application vary based on the year as shown in Figure 4-18. The years 2013 and 2016 had the highest proportion of canola fields with fungicide applied in the data. This is perhaps unsurprising as in 2012 the incidence of sclerotinia disease in canola was very high according to the Saskatchewan Canola Disease Survey which may have incentivised producers to invest more in fungicide the following year (Saskatchewan Canola Disease Survey, 2018). In the year 2016, the conditions were optimal for sclerotinia development across large portions of Saskatchewan which resulted in high sclerotinia incidence as reported by the Saskatchewan Canola Disease Survey (Government of Saskatchewan, 2019). Producer’s decisions to apply more fungicide in 2016 was likely in response to the wet conditions of 2016 and their previous experiences with high disease incidence in 2012. The incidence reports from the Saskatchewan Canola Disease Survey are shown in Figure 4-19 (SCIC, 2019).

Figure 4-18 Proportion of fungicide (=1) application observations over 2011-2019.



Source: (SCIC, 2019)

Figure 4-19 Sclerotinia incidence by region 2010-2018 based on Saskatchewan Canola Disease Survey.



Saskatchewan Canola Disease Survey - sclerotinia incidence by Region, 2010-2018

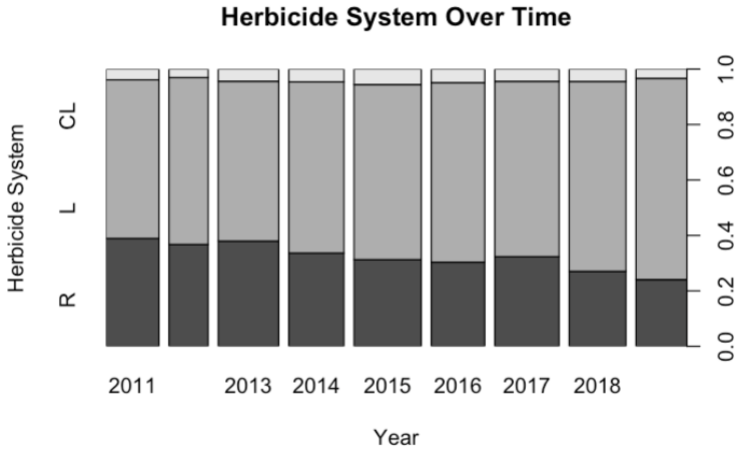
Year	North East	North West	East Central	West Central	South East	South West	Province
	Scerotinia stem rot disease incidence (%)						
2010	20.0	20.0	22.0	22.0	12.0	15.0	20.0
2011	11.0	6.0	10.0	10.0	2.2	10.5	9.0
2012	13.6	16.5	20.4	29.3	21.7	4.1	19.0
2013	3.0	1.0	6.0	8.0	4.0	7.0	5.0
2014	7.0	17.0	13.0	18.0	15.0	6.0	14.0
2015	8.0	10.0	5.0	6.0	7.0	6.0	7.0
2016	20.0	30.0	18.0	46.0	19.0	20.0	24.0
2017	4.0	5.3	1.8	2.1	0.6	1.0	3.4
2018	4.5	10.5	1.2	0.4	1.4	2.2	5.8
Average	**10.1**	**12.9**	**10.8**	**15.4**	**9.2**	**8.0**	**11.9**
Potential Yield Loss	5.1	6.5	5.4	7.7	4.6	4.0	6.0

Source: (Government of Saskatchewan, 2019)

4.4.9 *Variety herbicide system*

Canola hybrid varieties have been bred with different herbicide-tolerance including resistance to glyphosate, imidazoline and glufosinate. The herbicide-tolerance trait of canola varieties has been used to reduce weed pressure which can significantly increase yields (Harker, Blackshaw, Kirkland, et al., 2000; Harker, O'Donovan, Clayton, et al., 2008; Clayton, Harker, O'Donovan, et al., 2002). Previous research has also found different herbicide-tolerance systems have differing impacts on weed pressure and subsequent canola yields. Liu, Gan, and Poppy found that cultivars with the Liberty Link herbicide system were the highest yielding on average relative to Round-up Ready system, with a 700 kg/ha increase in yield (Liu, Gan, & Poppy, 2014). In the canola production model, varieties were categorized into herbicide system groups: Clearfield (imidazoline resistant), Liberty Link (glufosinate resistant) and Roundup Ready (glyphosate resistant). As shown in Figure 4-20, throughout the years 2011-2019 the majority of canola varieties grown in the dataset are Liberty Link varieties with the second most common being Roundup Ready, and a small portion of the observations being Clearfield varieties. There also appears to be an increasing proportion of Liberty Link canola varieties over the time period 2011 to 2019.

Figure 4-20 Proportion of herbicide system of variety in observations over 2011-2019.

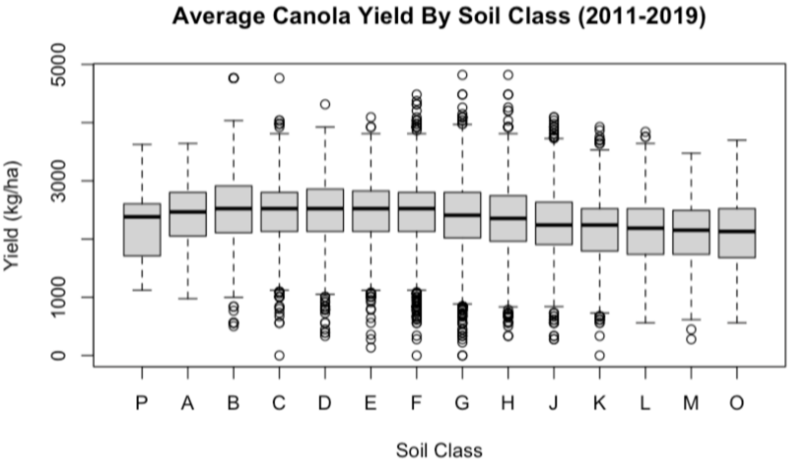


Note: R = RoundUp Ready, L = Liberty Link, CL = Clearfield
Source: (SCIC, 2019)

4.4.10 Soil productivity

Soil productivity is a very important factor in determining crop yield. The soil productivity classifications used by Saskatchewan Crop Insurance Corporation to adjust yields and premium rates are based on historical Saskatchewan Assessment Management Agency ratings. These soil productivity class ratings are denoted by letters of the alphabet with ‘A’ being the highest productivity soil and ‘P’ being the lowest productivity soil. As shown in Figure 4-21, the average yield of canola is reduced as the soil productivity rating moves from high to low productivity soil (A-P). In order to control for the soil productivity attributes of each field that determine canola yield, the SCIC soil productivity rating was included as a fixed effect within the model.

Figure 4-21 Canola yield observations by soil productivity classification over 2011-2019.



Source: (SCIC, 2019)

4.4.11 Producer x Year

The management factors that ultimately determine canola yield are numerous. Important management factors that determine crop yield have been found in the literature to include type of seeding equipment, seeding rate, seeding speed, row spacing, seeding depth, long-term crop rotation, weed control and residue management. Within the confines of available data for this project, all of the yield determining factors of canola could not be included in the model. Therefore, producer fixed-effects were included in the model in an attempt to control for unobservable management factors that may be affecting canola yield. For example, a producer who due to seeding equipment has a more ideal seed bed and plant distribution may outyield another producer with less ideal seeding equipment. In the data set over the years 2011-2019 there are 2,766 different producer IDs. Not all producers have canola fields in each year. Some producers in the sample are large producers with numerous canola fields each year while some are relatively smaller producers with as low as one canola field reported in a year. The yield response to nitrogen application has been shown in literature to vary based on the annual growing conditions (Angadi, Cutforth, McConkey, et al., 2004; Henry & MacDonald, 1978; Gan, et al., 2004). Annual fixed effects are included in the yield model to control for annual differences in growing conditions as well as other factors that vary by year. The years 2011-2019 are included in the selected sample, for a total of 8 crop years.

Producer interacted with year fixed effects were included in the model. Producer fixed effects are controlling for differences among different managers and farming operations that are numerous and greatly effect yield such as agronomic knowledge, crop scouting, seeding technology and harvest loses. Year fixed effects controls for temporal variation that is not otherwise accounted for in the model such as annual differences in climatic, insect and disease variables. Year by producer fixed effects controls for differences among managers across time. The reasoning to include producer x year FE in the model was to allow for producer's effect on yield to change over time. The effect producer management on yield could for various reasons vary year to year due to a variety of factors including experience, environmental conditions, equipment upgrades, available labour, etc. Due to the lack of available data on the important annual management factors that affect canola yield, producer x year fixed effects were considered for inclusion in the model.

Since a majority of producers do not vary their nitrogen rates by fields within years, it is important to consider whether the producers who vary their nitrogen rate by fields within a year are different than those producers who do not vary their nitrogen rates by. In Table 4-14 descriptive statistics are provided of the variation in nitrogen rates by individual producers within years. Only a minority of producers are varying nitrogen rates by field within a year (10.4 -16.5% of the selected data sample). Due to the very large original sample size, this would still result in over 7,000 observations. In a model where the fixed effect of producer x year is included, the model selects for producers that show variation in the nitrogen rate across fields within years, there may be selection bias. When comparing the average yields of the producers who show variation in nitrogen within years to those who do not, the average canola yields are very similar over the years 2011-2019 as shown in Table 4-15. When comparing the average nitrogen rate applied among producers who show variation in nitrogen within years relative to those who do not, the average nitrogen applied yields are slightly higher among producers who show variation in nitrogen within years, especially in 2019. Over the years 2011-2019 the average nitrogen rate in the selected sample was 105 kg ha^{-1}, which is slightly below the average of 108 kg ha^{-1} for only producers whose nitrogen rates vary across fields within years. Therefore, selecting for producers who show variation in nitrogen applied within a year may result in a slight upward bias as these producers appear to apply slightly more nitrogen yields on average than those in the selected sample.

Table 4-14 Descriptive statistics of variation of nitrogen rates by individual producers within years.

Year	Total Obs.	# of Prod.	# of Prod. With N Variation	% of Prod. with N Variation	# of Obs. with N Variation Among Prod.	% of Total Obs. with N Variation Among Prod.	Mean St.dev Among Prod. with N Variation (kg ha^{-1})	Mean Variation Among Prod. with N Variation (kg ha^{-1})
2019	4789	825	110	13.3	791	17	9.9	158
2018	5431	1006	105	10.4	752	14	11.2	225
2017	6048	1064	118	11.1	756	13	9.1	134
2016	5024	976	105	10.8	631	13	10	210
2015	6322	1228	146	11.9	979	15	9.6	163
2014	5189	1034	121	11.7	756	15	9.4	170
2013	5692	1207	143	11.8	863	15	8.1	104
2012	3681	789	102	12.9	647	18	10.9	202
2011	4973	1037	171	16.5	1051	21	9.8	146
Avg.				**12.3**		**15**	**9.8**	**168**
Total	**47149**	**9166**	**1121**		**7226**			

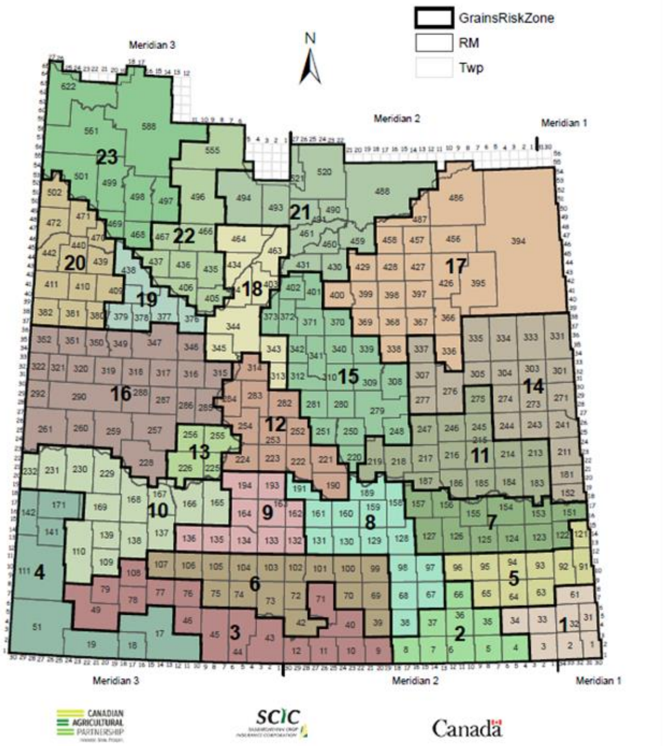
Table 4-15 Yield and nitrogen rate means of producers who vary nitrogen across fields within years compared to the overall yield and nitrogen sample mean.

Year	**Mean Yields of Selected Sample (kg ha^{-1})**	**Mean Yields Among Prod. with N Variation within Years (kg ha^{-1})**	**Mean Nitrogen Applied of Sample (kg ha^{-1})**	**Mean Nitrogen Among Prod. With N Variation within Years (kg ha^{-1})**
2011	2167	2172	94	95
2019	2686	2750	116	121
2011-2019	2371	2384	105	108

4.4.12 Risk zone

There are many different agro-ecological conditions that impact canola production, and these conditions can vary significantly between regions of Saskatchewan within a growing season and across years. The grain risk zones are classified by Saskatchewan Crop Insurance Corporation and refer to broad differences in agro-ecological conditions between geographical areas throughout Saskatchewan. The grain risk zones are separated into 23 groups and are utilized by SCIC to assess weather-elated crop production risks. A map of the grain risk zones is shown in Figure 4-22. Of the 23 grain risk zones, 20 grain risk zones were included in the final data set used in analysis. There were an insufficient number of observations in risk zones 3, 4 and 13 and therefore these risk zones were omitted due to producer privacy reasons. In order to control for the many different agr-ecological conditions between the grain risk zones of Saskatchewan, risk zone was included as a fixed effect in the model.

Figure 4-22 Grain risk zone regions of Saskatchewan as classified by SCIC.



Source: (Saskatchewan Crop Insurance Corporation, 2022)

4.5 Summary Statistics of Model Variables

A table of the selected sample summary statistics of the variables over the years 2011-2019 that are included in the canola yield model are shown in Table 4-16. The mean canola yield in the sample was 2372 kg ha^{-1} while the mean nitrogen applied reported in the sample was 109 kg ha^{-1}. The majority of observations (57.8%) in the sample were canola fields on previous crop cereal followed by 32.5% of canola fields observations were on previous crop oilseed. Canola fields seeded on pulse previous crop were a small percentage of the sample observations at 9.70%. The average seeding date in the sample was 9.86 days after May 14, which is equivalent to roughly May 24th. The majority of the sample canola fields did not have a fungicide applied in-crop, with only 30.90% of observations having a fungicide applied. The mean three-year historical average precipitation was 274.2 mm. However, a wide range of historical average precipitations are included in the sample, ranging from 123mm to 481mm. The average variety index of the sample is 93.3% of the average yield of the reference variety (L252). The majority of the canola fields (63.20%) were seeded with canola varieties with Liberty Link herbicide system technology. The next most common herbicide system was Roundup Ready (63.20%) followed by Clearfield (4.40%).

Table 4-16 Summary statistics of variables included in the production function.

Variable	**N**	**Mean/Mode**	**Std. Dev.**	**Min**	**Max**
Yield (kg ha^{-1})	47059	2371.5	559.6	0.0	4818.5
Nitrogen (kg ha^{-1})	47059	109.0	25.6	40.4	297.1
Phosphorous	47059	32.3	10.7	0.0	89.7
Potassium	47059	4.3	8.5	0.0	56.1
Sulphur	47059	20.8	10.2	0.0	74.0
Previous crop	47059				
Pulse	4586	9.70%			
Cereal	27182	57.80%			
Oilseed	15291	32.50%			
Seeding Date	47059	9.68	7.661	-19	28
Fungicide Applied	14531	30.90%			
Avg precipitation	47059	274.2	51.3	123.0	481.1
GS Precipitation	47059	242.8	75.1	0.8	540.8
Variety index	47059	93.3	9.1	44.1	133.1
Herbicide system	47059				
... Clearfield	2055	4.40%			
... Liberty Link	29752	63.20%			
... Roundup Ready	15252	32.40%			

Source: (Saskatchewan Crop Insurance Corporation, 2022)

4.6 Summary

This chapter provided an overview of the data sources, including a discussion of the representativeness of the data which was followed by descriptions of the variables.

The data used in this thesis includes SCIC management data, Environment Canada precipitation data, Government of Canada variety data, as well as annual nitrogen and canola price data from Saskatchewan Ministry of Agriculture and Alberta Agriculture and Forestry. The representativeness of the selected data sample was investigated by comparing the selected data sample to the provincial, crop insurance and SMP reported seeded acre and yields of canola. The selected sample is a large data set, representing 7% of provincial reported canola area seeded from 2011-2019. However, the comparison of the selected sample to provincial reported production suggests the data set may be upwardly biased for canola yields. Additionally, when including producer x year fixed effects in the estimation of the canola production function the data is selected for producers who vary nitrogen applied rates within year which may also result in a slight upward bias. Finally, a description of the variables in the model including summary statistics was provided. Now that the data used in analysis has been described, the next chapter includes the estimation process followed by the regression results and optimal nitrogen use estimates.

CHAPTER 5 THE ESTIMATION PROCESS, REGRESSION RESULTS & OPTIMAL N USE ESTIMATES

5.1 Introduction

This section describes the estimation process, regression results and optimal nitrogen rate estimates. The estimation process includes an overview of the data analysis, model specification, previous regression results and assesses residuals and predicted values of the chosen model. The regression results section includes the presentation of the canola production model coefficient estimates with particular emphasis on the canola yield response to nitrogen. The optimal nitrogen rate estimates are provided with equations individual producers can use to estimate their own optimal nitrogen rate. The economic optimal nitrogen rate is estimated for various price scenarios, previous crops and variety indexes and includes a robustness check with an alternative model. A discussion of the economic optimal nitrogen rates then concludes this chapter.

5.2 The Estimation Process

5.2.1 Data Analysis

The data analysis was completed using the statistical program R version 4.0.5. The *fixest* package (Bergé, 2018) was used for the OLS regression analysis which included fixed effects by using the *feols* function. The *marginaleffects* package (Arel-Bundock, 2022) was used for the prediction, average and grouped marginal effects, and delta method tasks using the *predictions, marginal means,* and *deltamethod* functions respectively.

5.2.2 Model Specification

As described in Chapter 3, the estimated production function is:

5-1

$$\gamma_{it} = f(v_{it}, x_{it}, z_{it}),$$

where v_{it} is a vector comprised of variable inputs and the vector x_{it} is comprised of management factors. A vector of agro-ecological conditions is denoted by z_{it}. The canola production function model was developed on the basis of canola agronomic theory and the factors that affect canola yield. A review of canola agronomic research is outlined in section 2.4 of the literature review. Additionally, Sheahan, Black and Jayne (2013) developed an econometric model used to estimate the marginal and average products of nitrogen in the context of corn in Kenya. This econometric model was used as a reference throughout the production function model development of this thesis (Sheahan, Black, & Jayne, 2013). Table 4-5 includes a full list of the variables included in the production function model. Variable inputs included fertilizer applied and fungicide applied. Management factors included crop rotation, variety chosen and seeding date. Agro-ecological conditions include soil moisture, growing season precipitation, soil productivity and grain cropping risk zone region. In this model, soil moisture is proxied by the previous three-year average growing season precipitation of the closest weather station to a field in a given year.

The estimated model a modified quadratic with fixed effects as described by equation:

5-2

$$\begin{aligned}
&\mathrm{E}(\gamma_{it}) = \beta_1 N_{it} + \beta_2 {N_{it}}^2 + \beta_3 P_{it} + \beta_4 K_{it} + \beta_5 S_{it} + \beta_6 VarietyIndex_{it} + \\
&\beta_7 LibertyLink_{it} + \beta_8 RoundupReady_{it} + \beta_9 AvgPrecip_{it} + \beta_{10} {AvgPrecip_{it}}^2 + \\
&\beta_{11} GSPrecip_{it} + \beta_{12} {GSPrecip_{it}}^2\ \beta_{13} SeedingDate_{it} + \beta_{14} {SeedingDate_{it}}^2 + \\
&\beta_{15} Fungicide_{it} + \beta_{16} CerealCrop_{i(t-1)} + \beta_{17} PulseCrop_{i(t-1)} + \beta_{18} VarietyIndex_{it} * \\
&LibertyLink_{it} + \beta_{19} VarietyIndex_{it} * RoundupReady_{it} + \beta_{20} N_{it} * CerealCrop\ _{i(t-1)} + \\
&\beta_{21} N_{it} * PulseCrop_{i(t-1)} + \beta_{22} N_{it} * VarietyIndex_{it} + \beta_{23} SoilClass_i + \beta_{24} Risk\ Zone_i + \\
&\beta_{25} Producer_{it} * Year_t + \epsilon_{it}
\end{aligned}$$

where the variables nitrogen (N), phosphorous (P), potassium (K), sulphur (S), variety index, herbicide system, previous crop, seeding date and fungicide vary by individual field. The average historical growing season precipitation (which proxies soil moisture) and growing season precipitation vary by field on by closest reporting weather station within a year. For nitrogen, average precipitation and seeding date, the squared terms were included). The fixed effects of producer by year, risk zone and soil class are included to control for the variation attributed to differences among soil classes, risk zones and producer by year that are not otherwise accounted for by the other variables included in the model.

The variables in the production function model are included based on agronomic theory. As discussed in Section 2.4, nitrogen, phosphorous, potassium, sulphur, variety, herbicide system, previous crop, seeding date, fungicide, available water, soil characteristics, spatial factors and various management factors can all impact canola yield. For nitrogen, average precipitation and seeding date, the squared terms were included based on agronomic theory and the significance of the squared term estimates ($p<0.05$). Literature has indicated that extreme values of these variables have generally been found to result in lower canola yields. These variables contribute to canola yield positively with diminishing marginal yield up to a point, after which then negative effects on canola yield occur. Thus, the quadratic form for these variables was included.

Not all variables that affect canola yield are included in the model due to limited data availability. Therefore, fixed effects of producer by year, risk zone and soil class are included to control for the variation attributed to differences among soil classes, risk zones and producer by year that are not otherwise accounted for by the other variables included in the model. The soil class fixed effect is accounting for differences in soil capability. The risk zone fixed effect is controlling for spatial variation that effects canola yield that is not otherwise accounted for in the model. Producer fixed effects are controlling for differences among different managers and farming operations that effect yield such as agronomic management and equipment. Year fixed effects controls for temporal variation that is not otherwise accounted for in the model. Finally, year by producer fixed effects controls for differences among managers across time. As previously discussed in 3.3.2, the estimates from the canola production are limited by the potential for bias in the case of correlation between input levels and unobserved time-varying producer-specific shocks. The use of fixed effects does not address productivity shocks that are not fixed over time, in which case the estimates of this production function may be biased (Levinsohn & Petrin, 2003).

5.2.3 Correlation Matrix

The correlation matrix of the continuous variables included in the production function model can be found in Table 5-1. Yield is most highly correlated with nitrogen and variety index variables, followed by phosphorous and sulphur. Nitrogen is most highly correlated with sulphur, phosphorous, and yield.

Table 5-1 Correlation matrix of continuous variables in the production function model.

	Yield	**N**	**P**	**K**	**S**	**Seeding date**	**Avg Precip**	**GS Precip**	**Variety index**
Yield	1.00	0.41	0.26	0.16	0.26	-0.09	-0.18	-0.22	0.41
N	0.41	1.00	0.42	0.20	0.45	-0.02	-0.12	-0.08	0.32
P	0.26	0.42	1.00	0.17	0.30	-0.03	-0.12	-0.08	0.26
K	0.16	0.20	0.17	1.00	0.23	0.07	0.03	0.01	0.12
S	0.26	0.45	0.30	0.23	1.00	0.02	-0.04	-0.03	0.18
Seeding date	-0.09	-0.02	-0.03	0.07	0.02	1.00	0.23	0.08	-0.14
Avg Precip	-0.18	-0.12	-0.12	0.03	-0.04	0.23	1.00	0.15	-0.40
GS Precip	-0.22	-0.08	-0.75	0.01	-0.03	0.08	0.15	1.00	-0.28
Variety Index	0.41	0.32	0.26	0.12	0.18	-0.14	-0.40	-0.28	1.00

5.2.4 Model Development

Before presenting the results of the regression model, the process of model development is first described. First is a discussion on the testing and inclusion of interaction terms. This is followed by a discussion of the fixed effects included within the model including alternative models explored as well as associated issues. This section is concluded by testing for homoskedasticity with a discussion on the choice of standard errors.

5.2.4.1 Interaction Terms

In developing the canola production function model, interaction terms were explored. The interaction effects between nitrogen and other inputs in the canola production function is of particular importance to this study as the optimal nitrogen application rate is a focus which is dependent on the substitutability of nitrogen with other inputs. Therefore, numerous interaction terms between nitrogen and other inputs were tested for statistical significance ($p < 0.05$).

Interaction terms between nitrogen and fungicide, phosphorous, sulphur and potassium were tested however no statistically significant interaction effects were found. These results indicate that nitrogen is independent of both fungicide and the other fertility inputs in the canola production function. Previous agronomic research has found evidence of nitrogen and sulphur being compliments in canola production (Mahli & Gill, 2007) . However, there was no evidence of a statistically significant interaction between nitrogen and sulphur in the model and thus no N x S interaction term was included. However, a statistically significant interaction between nitrogen and variety index was estimated indicating a complimentary relationship. A Wald test was performed to assess the appropriateness of including the nitrogen x variety index interaction int the model. The null hypothesis that nitrogen x variety index should not be included in the model was rejected (p value < 2.2e-16). This is perhaps unsurprising, as in the literature different varieties has been found to affect the yield responsiveness of canola to nitrogen with higher yielding canola requiring high rates of nitrogen (Cutforth, et al., 2009). Another significant interaction was found between nitrogen and previous crop type. The Wald test results suggest the null hypothesis that nitrogen x previous crop type should not be included in the model be rejected (p value < 2.2e-16). The estimates of the interaction effect between nitrogen and previous crop type indicate that previous crop types of pulse are a substitute for nitrogen applied. This finding is supported in the literature where nitrogen fixing crops can increase soil residual nitrogen (O'Donovan, et al., 2014). Given that the previous crop type is assumed to be fixed in the short run, the EONR are calculated for each previous crop type. Nitrogen is not found to be a substitutable input with any other inputs in the estimated canola production function based on these findings.

Within the agronomic literature, numerous interaction effects have been found within the canola production function. Previous studies have found that environmental factors can alter the canola nitrogen response. An interaction between nitrogen and precipitation was tested as previous works have indicated that the canola yield response to nitrogen can vary based on the moisture conditions of the growing season (Mahli, et al., 2007). However, no statistically significant effect was found on the interaction of nitrogen with either growing season precipitation or 3-year average historical precipitation (a proxy variable for soil moisture). Previous literature has also indicated that the impact of fungicide on canola yield may be dependent on growing season precipitation which often dictates disease pressure (Kutcher &

Wolf, 2006). However, no statistically significant effect was found on the interaction of fungicide with either growing season precipitation or 3-year average historical precipitation. An additional interaction of herbicide system with variety index was also tested based on agronomic theory. Previous literature has also indicated the effect of herbicide system associated with the variety chosen can impact canola yield (Liu, Gan, & Poppy, 2014). A statistically significant effect was found on the interaction between herbicide system of variety and the variety index and was therefore included in the model. The Wald test results suggest the null hypothesis that variety index x herbicide system of variety should not be included in the model be rejected (p value < 2.2e-16). Overall, the interactions of nitrogen by variety index and previous crop type were included based on agronomic theory and statistical significance (Table 5-2).

Table 5-2 Wald test results that supported inclusion of the interaction terms in the canola production function model.

Interaction	**F stat**	**H_O = Do not include in model**
N x Variety Index	F stat: 24.9	Reject null (p < 2.2e-16)
N x Prev. Crop Type	F stat: 45.5	Reject null (p < 2.2e-16)
Variety Index x Herbicide System	F stat: 32.7	Reject null (p < 2.2e-16)

5.2.4.2 Fixed Effects

The fixed effects of producer by year, risk zone and soil class were included to control for unobservable variables that effect canola yield including soil capability, spatial and temporal variation as well as management factors across time. Wald tests were also performed to assess the appropriateness of including these variables as fixed effects in the model. Wald tests for models with fixed effects for soil class, risk zone and year by producer indicate that the null hypothesis that each fixed effect should not be included in the model was rejected (p value < 2.2e-16). The stepwise impact of including fixed effects in the regression are shown in Table 5.3. Without any fixed effects, 35.1% of the variation in canola yield is explained by the production function model. The addition of each fixed effect increases the adjusted r-squared value, from 35.1% with no fixed effects to 80.3% when fixed effects of soil class, risk zone and producer by year (Model 7) are included. Before choosing Model 7 to derive the canola production function estimates used for analysis, numerous alternative models were assessed for their suitability, the process of which is discussed next.

The inclusion of year x producer fixed effects was included to control for differences among managers across time. The theory behind including year x producer fixed in the model was that it was important to allow for producer's effect on yield to change over time. It seems likely that the effect of producer management on yield varies year to year dependent on experience, environmental conditions, equipment upgrades, available labour, etc. Individual producer management decisions and farming technologies may vary drastically year to year. For example, a producer who in one year has issues with their seeder that results in canola yield loses may in the next year upgrade their seeding equipment which results in higher canola yields. Due to the lack of available data on the important year to year management factors that affect canola yield, year x producer fixed effect was included originally in the model to control for some of these factors.

The drawbacks of including year x producer FE in the model is that only a minority of producers are varying nitrogen rates by field within a year (10.4 - 16.5% of the selected data sample). Due to the very large original sample size, this would still result in over 7,000 observations. However, the results in selecting for producers that show variation in the nitrogen rate across fields within years, and thus there may be selection bias. When comparing the yields and nitrogen rates of the selected sample to the sample with only producers that show variation in the nitrogen rate across fields within years, those producers that vary nitrogen have only slightly higher nitrogen rates and yields (Table 4-15). However, the larger issue is whether the source of the variation of nitrogen rates within years by individual producers endogenous or exogenous the canola yield function. Before including year x producer fixed effects in the model, one must consider the factors that drive variation in nitrogen application across fields within a year for a producer. If the source of the variation is endogenous to the canola yield production function, the model estimates would be biased. Two potential reasons why individual producers may vary nitrogen rates applied across fields within a year that are exogenous are 1) Logistics and 2) Experimentation. The logistical challenge that producers face in applying nitrogen to fields may be a reason why producers are applying different nitrogen rates on different fields within a year. This is represented in equation 3-12 where variable inputs incur a constraint that limits the maximum rate applied to an individual field within a given year. Due to the importance of timeliness at seeding where producers have a small window of time to get the crop in, there are often constraints on time in hauling and applying nitrogen. Producers may vary rates across fields based on the given constraint of available time and labour. An example of this may be for a producer who applies a portion of nitrogen to their fields in the fall to reduce time at seeding. If the weather in the fall only allows the producer to apply nitrogen to some of their fields, due to the time constraints at seeding, the producer may have a range of nitrogen rates across their fields. Producers may also be applying varying nitrogen rates to differing fields within a year due to producers experimenting with on-farm fertility rates. The recommended nitrogen rates by agronomists over the years have been trending upwards. For example, in 2015 the recommended rate for the Brown soil zone was 80 kg N /ha, while in 2019 the recommended rate for the Brown soil zone was 102 kg N/ha (Saskatchewan Ministry of Agriculture, 2022). Due to the evolving recommended nitrogen rates over time, producers who are varying their nitrogen rates across fields may be experimenting with fertility in presence of these changing recommended rates. Logistical and experimental reasons are potential sources of exogenous variation.

In light of the issue of potential endogeneity in the source of nitrogen rate variation within a year by individual producers, an alternative model that includes risk zone x year fixed effects instead of producer x year fixed effects was considered. In this model, several of the estimated optimal nitrogen rates seem quite low relative to the recommended rates. Using the 2012 average cost ratio and the variety index of 84%, the estimated optimal is 42 kg N ha^{-1} for previous crop type pulse (Table B.3). Very few producers in the sample are applying nitrogen at these low rates and this estimated EONR is nearly half the recommended agronomic nitrogen rates for Saskatchewan in the 2012 crop planning guide which ranged from 70-80 kg N ha^{-1} (Saskatchewan Ministry of Agriculture, 2022). Ultimately, the producer x year model was chosen for the analysis of this thesis. However, due to the potential endogeneity in the source of nitrogen rate variation within a year by individual producers a robustness check is included in the form of an alternative model which includes a year x risk zone fixed effect instead of the a year x producer fixed effect in section 5.5.4.

Consideration was also given to an alternative model included a variable of management index instead of producer fixed effects. Initially, a management index was included to parse out the estimated effect of producer management on canola yields. The management index was calculated as a percentage of an individual producer’s average historical canola yield relative to the average canola yield of the producer's risk zone. This alternative model was estimated and is shown in Table B.1 with the resulting estimated optimal nitrogen rates from this alternative model shown in Table B.1. The coefficient estimates estimated from a management index model were very different than those estimated from a model with producer fixed effects. The resulting estimated optimal nitrogen rates estimated from the management index model were significantly larger than those estimated with producer fixed effects. The inclusion of producer fixed effects as opposed to the management index resulted in higher R^2 values and more reasonable economic optimal nitrogen estimates. The estimated optimal nitrogen rate using the model with the management index is 197 kg N ha^{-1} at the 2019 average cost ratio and the average 2019 variety index of 101.6%. That is well outside the agronomic recommended nitrogen rates for Saskatchewan in the 2019 crop planning guide which ranged from (102 – 111 kg N ha^{-1}) and very few producers in the sample are applying nitrogen at these high rates. Ultimately, the benefit of controlling for unobservable management factors that affect yield that are numerous between managers through a producer fixed effect was seen as outweighing the potential benefit of including a management index. Including a management index in the model would allow for an estimation of the effect of producer management on canola yields. However, the focus of this thesis was not estimating producer management effect of canola yield, but instead the effect of nitrogen and estimating the optimal nitrogen application rate. Therefore, producer fixed effects were used in the model chosen for analysis.

Throughout the development of the model, the inclusion of variety fixed effects was also considered. A comparison of the different models with variety fixed effects relative to a variety index are shown in Table B.2 of Appendix B. There were minor differences in the coefficient estimates and the resulting estimated optimal nitrogen rate when comparing the two models. Therefore, the inclusion of the variety index in the model was ultimately decided on in order to estimate the effect of variety index and the herbicide system of the variety on canola yield.

Table 5-3 Stepwise inclusion of fixed effects.

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Intercept	1070 (166)***						
Nitrogen (N)	0.300 (0.977)	−0.325 (0.959)	0.187 (0.922)	−3.323 (0.909)***	−7.56 (0.967)***	−3.78 (0.958)***	1.86 (1.81)
N^2	−0.0331 (0.00259)***	−0.030 (0.00255)***	−0.0251 (0.00257)***	−0.0245 (0.00245)***	−0.00831 (0.00297)**	−0.0120 (0.00286)***	−0.0140 (0.00535)**
Phosphorous	1.64 (0.233)***	1.70 (0.231)***	2.17 (0.231)***	1.70 (0.229)***	0.242 (0.282)	0.428 (0.270)	2.34 (1.02)*
Potassium	2.97 (0.256)***	3.18 (0.254)***	2.45 (0.259)***	2.51 (0.252)***	2.03 (0.368)***	1.49 (0.361)***	3.36 (1.18)**
Sulphur	3.44 (0.242)***	3.37 (0.242)***	2.36 (0.241)***	2.40 (0.234)***	−0.490 (0.318)	−0.248 (0.305)	2.77 (0.973)**
Variety Index	1.776 (1.70)	3.04 (1.682)+	6.50 (1.63)***	−2.32 (1.61)	−4.76 (1.65)**	−0.510 (1.59)	4.65 (2.31)*
Liberty Link Dummy	242 (129)+	318 (129)*	331 (124)**	575 (122)***	467 (129)***	385 (124)**	529 (155)***
Roundup Ready Dummy	−83.9 (128)	8.49 (128)	161 (123)	238 (121)*	224 (127)+	334 (122)**	419 (153)**
Avg Precipitation (AP)	−2.78 (0.286)***	−3.28 (0.282)***	−3.12 (0.295)***	0.140 (0.306)	1.08 (0.324)***	2.25 (0.394)***	1.86 (0.771)*
AP^2	0.00425 (0.00510)***	0.00507 (0.000500)***	0.00519 (0.000520)***	−0.000511 (0.000540)	−0.00206 (0.000580)***	−0.004 (0.001)***	−0.00272 (0.00142)+
GS Precipitation (GSP)	4.20 (0.161)***	4.11 (0.159)***	3.44 (0.152)***	3.01 (0.152)***	3.17 (0.141)***	2.291 (0.156)***	0.469 (0.352)
GSP^2	−0.0100 (0.00031)***	−0.00989 (0.000300)***	−0.00854 (0.000291)***	−0.00632 (0.000272)***	−0.00638 (0.000261)***	−0.00429 (0.000272)***	−0.00128 (0.00065)*
Seeding Date	6.274 (0.610)***	5.32 (0.609)***	−0.793 (0.618)	0.436 (0.585)	1.44 (0.629)*	2.72 (0.635)***	4.79 (1.30)***
Seeding Date^2	−0.489 (0.0283)***	−0.460 (0.0282)***	−0.256 (0.0281)***	−0.236 (0.0264)***	−0.209 (0.0275)***	−0.284 (0.0275)***	−0.376 (0.0691)***
Fungicide Dummy	196 (4.75)***	189 (4.71)***	198 (4.62)***	187 (4.42)***	161 (5.10)***	140 (4.95)***	152 (9.01)***
Cereal Prev. crop Dummy	79.0 (21.9)***	74.6 (21.5)***	66.6 (20.8)**	−7.33 (20.2)	−1.90 (18.5)	12.3 (17.7)	21.5 (19.7)
Pulse Prev. crop Dummy	71.5 (36.6)+	94.2 (36.4)**	92.2 (34.8)**	40.0 (33.3)	5.96 (30.4)	28.8 (28.7)	63.9 (29.5)*
Variety Index x Liberty	−2.74 (1.38)*	−3.52 (1.37)*	−3.28 (1.32)*	−5.60 (1.29)***	−4.71 (1.36)***	−3.80 (1.30)**	−4.91 (1.63)**
Variety Index x Roundup	0.752 (1.37)	−0.170 (1.36)	−1.62 (1.31)	−2.64 (1.29)*	−2.52 (1.35)+	−3.71 (1.29)**	−4.26 (1.61)**
N x Cereal Prev.crop	−0.376 (0.195)+	−0.373 (0.193)+	−0.249 (0.187)	−0.0925 (0.183)	−0.107 (0.166)	−0.125 (0.158)	−0.155 (0.176)
N x Pulse Prev.crop	−0.413 (0.333)	−0.586 (0.331)+	−0.286 (0.318)	−0.158 (0.305)	0.00453 (0.276)	−0.116 (0.259)	−0.482 (0.268)+
N x Variety Index	0.135 (0.0104)***	0.129 (0.010)***	0.109 (0.00991)***	0.142 (00962)***	0.127 (0.00938)***	0.0939 (0.00904)***	0.0444 (0.0155)**
R2	0.351	0.363	0.407	0.466	0.65	0.69	0.853
R2 Adj.	0.35	0.363	0.406	0.465	0.628	0.669	0.803
R2 Within		0.342	0.342	0.206	0.071	0.056	0.038
FE: Soil Class		X	X	X	X	X	X
FE: Risk Zone			X	X	X		X
FE: Year				X	X		
FE: Producer					X	X	
FE: Year x Risk Zone						X	
FE: Year x Producer							X

5.2.4.3 Homoscedasticity

The model is tested for the assumption of homoscedasticity using a Breusch-Pagan test. The results indicate that the null hypothesis of homoscedasticity be rejected (p value < 2.2e-16). This test suggests that the standard errors of the OLS estimates are biased. The non-constant variance in the data set suggests the use of robust standard errors, a common solution to heteroskedasticity (Wooldridge, 2010). The use of clustered standard errors was also considered, with thought given to clustering at the producer level. Clustered standard errors are often used in econometric models when unobserved components in outcomes for units within clusters are correlated (Abadie, Athey, Imbens, et al., 2017). Put differently, clustered standard errors are often considered in econometrics when observations within each group are not independently and identically distributed. However, there is often confusion of when to use clustered standard errors. In order to clarify the role of clustering adjustments to standard errors, Abadie, Athey, Imbens, et al. (2017) outline the two conditions under which standard errors should be clustered in the case of a fixed effect model. The conditions are to cluster if there is (i) both clustering in the assignment and there is heterogeneity in the treatment effects or (ii) both clustering in the sampling and there is heterogeneity in the treatment effects (Abadie, Athey, Imbens, et al., 2017).

Consider the case of a model that includes only producer fixed effects (Model 5 as shown in Table 5-3). While the inclusion of producer fixed effects controls for unobserved heterogeneity between different producers, there may still be unexplained variation in yield within the producer group that is correlated with time. Therefore, there is likely heterogeneity in the effect of producers over time. For example, it seems likely that many producers are improving equipment and managerial ability over time which in turn positively increases the producer effect on canola yield over time. Therefore, at the producer level, we may assume that there is temporal serial correlation in the error terms within producers. Using Abadie, Athey, Imbens et al. (2017) conditions to cluster in the case of fixed effects, the clustering in the sampling of producers and the heterogenity in the producer effect likely would warrant the use of clustered standard errors for Model 5 in Table 5-2. However, the model chosen for analysis includes year by producer fixed effects (Model 7 in Table 5-3). In this model, unobserved heterogeneity in the effect of producers over time is dealt with by treating each producer in each year as a different group.

Therefore, it is assumed that heterogeneity in the effect of each year x producer is less likely and robust standard errors were used as opposed to clustered standard errors (Abadie, Athey, Imbens, et al., 2017).

5.2.4.4 Residuals and Predicted Values

To assess the appropriateness of the functional form of Model 7 in Table 5-3, scatter plots of the residuals vs. the fitted values of the model are shown in Figure 5-1. In Figure 5-2 the predicted model yield is plotted versus the observed yield in the data set. Both scatter plots indicate the appropriateness of the functional form chosen.

Figure 5-1 Residuals vs. fitted values of canola production function model.

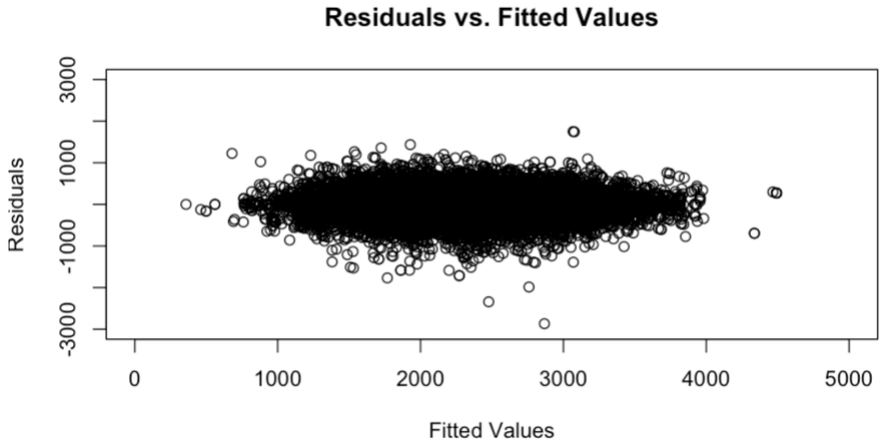
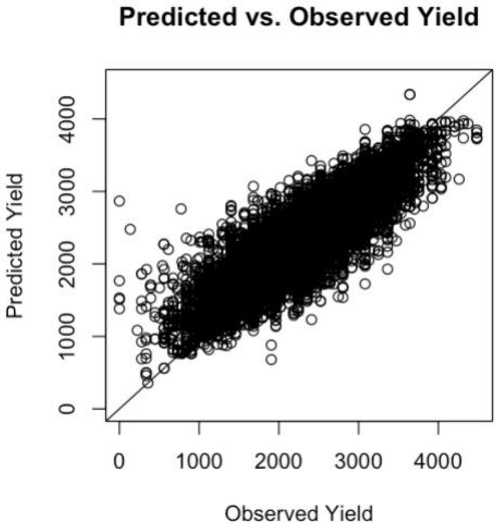


Figure 5-2 Predicted model yield vs. observed yield.



The predicted yields from Model 6 compared to the observed mean in the data by previous crop type are shown in Table 5-4. The predicted yields are the average predicted yields based on the means of the continuous variables and the modes of the categorical variables in the model as shown in Table 5-3. For the producer fixed effects, an average producer was chosen based on an individual average canola yield that was closest to the overall canola yield average of the sample which was (2372 kg ha^{-1}). In Table 5-4, the predicted yield from the production function model is fairly close to the observed mean yields. The standard error of the predicted yield is near 10% of the predicted yield value.

Table 5-3 Means of continuous variables and modes of categorical variables.

Variable	**Mean/Mode**
Nitrogen	109.97
Phosphorous	32.33
Potassium	4.28
Sulphur	20.84
Variety Index	93.28
Herbicide System	Liberty Link
Average Precip	274
GS Precip	242
Seeding date	9.68
Fungicide	0
Previous crop	Cereal
Producer	Avg. Producer (avg yield of 2400 kg ha^{-1})
Year	2015
Risk zone	17
Soil class	G

Table 5-4 Observed mean canola yields compared to the average predicted yields of the production function model.

Prev. crop	**Obs. Mean**	**Pred. Yield**[1]	**std.error**	**statistic**	**p.value**	**conf.low**	**conf.high**
pulse	2386	2362	251.32	9.40	5.56E-21	1869	2854
cereal	2364	2355	251.25	9.37	7.02E-21	1863	2848
oilseed	2381	2350	251.19	9.36	8.20E-21	1858	2843

[1] Predicted yields based on the means and modes of all other variables which are shown in Table 5-3.

5.3 Regression Results

The production function estimates can be found in Table 5-6. As some variables, such as nitrogen, appear multiple times in the regression model, the average marginal effects (AMEs) for each variable are reported to aid in interpretation. The AMEs of the production function variables are shown in Table 5-5. The AMEs estimate the partial effect of an independent variable on the dependent variable using every observed value of the other covariates then average across the resulting effect estimates. This is opposed to the marginal effects at the means (MEMs), which is the computed marginal effect over the means of the covariates. AMEs are useful because they produce a single quantity summary that reflects the full distribution of covariates, unlike MEMs. Within the regression model there are interaction terms as shown in Table 5-6. The marginal effects of variables that are included in interaction terms are dependent on the level of the other inputs in the interaction. Therefore, the average marginal effect reported in Table 5-5 incorporates these effects by calculating the marginal effect of each variable at the observed input levels and then averages these marginal effects across all observations.

Table 5-5 Average marginal effects (AME) of the production function variables.

Term	Contrast	Effect	Std.Error		p value
Phosphorous	dY/dX	2.34	1.02	*	2.17E-02
Potassium	dY/dX	3.36	1.18	**	4.41E-03
Sulphur	dY/dX	2.76	0.97	**	4.47E-03
Variety Index	dY/dX	5.01	0.44	***	2.68E-30
Herbicide system	L - CL	71.2	12.22	***	5.78E-09
Herbicide system	R - CL	22.2	12.60	+	7.84E-02
Avg. Precipitation	dY/dX	0.37	0.16	*	2.18E-02
GS Precipitation	dY/dX	-0.15	0.13		2.34E-01
Seeding Date	dY/dX	-2.50	0.86	**	3.19E-03
Fungicide	1 - 0	152	9.01	***	4.15E-64
Previous crop	cereal - oilseed	4.61	4.45		2.99E-01
Previous crop	pulse - oilseed	11.3	6.66	+	9.00E-02
Nitrogen	dY/dX	2.82	0.42	***	1.20E-12

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5-6 Production function estimation results with dependent variable average canola yield of field (kg ha^{-1}).

Variables	**Description**	**Estimates**
P	Applied actual phosphorous (kg ha^{-1})	2.34 (1.02)*
K	Applied actual potassium (kg ha^{-1})	3.36 (1.18)**
S	Applied actual sulphur (kg ha^{-1})	2.77 (0.973)**
Variety Index	Variety grown yield % of the check	4.66 (2.31)*
LL (=1)	Dummy Liberty Link variety	529 (155)***
RR (=1)	Dummy Roundup Ready variety	419(153)**
Variety Index x LL		−4.91 (1.63)**
Variety Index x RR		−4.26 (1.61)**
Avg. Precip	Average historical growing season precipitation(mm)	1.86 (0.771)*
Avg. Precip^2		−0.00272 (0.00142)+
GS Precip	Growing season precipitation (mm)	0.469 (0.352)
GS Precip^2		-0.00128 (0.0000651)*
Seeding Date	Seeding date (days after May 14)	4.79 (1.30)***
Seeding Date^2		−0.376 (0.0691)***
Fungicide (=1)	Dummy fungicide application	152 (9.01)***
Prev.Crop Cereal (=1)	Dummy prev.crop type cereal	21.5 (19.7)
Prev. Crop Pulse (=1)	Dummy prev.crop type pulse	63.9 (29.5)*
N	Applied actual nitrogen (kg ha^{-1})	1.86 (1.81)
N^2		−0.0140 (0.00535)**
N x Prev. Crop Cereal		−0.155 (0.176)
N x Prev. Crop Pulse		−0.482 (0.268)+
N x Variety Index		0.0444 (0.0155)**
Num. Obs.		47059
R2		0.853
R2 Adj.		0.803
R2 Within		0.038
Std.Errors		Hetero-robust
FE: Producer*Year		X
FE: Risk zone		X
FE: Soil class		X

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

5.4 Discussion of Regression Results

5.4.1 Phosphorous, Potassium and Sulphur

The nutrient variables of phosphorous, potassium and sulphur all had a statistically significant effect on canola yield ($p < 0.05$, $p < 0.01$, $p < 0.01$). For every 1 kg ha^{-1} of applied nutrients, the resulting estimated increase in canola yield was 2.34, 3.36 and 2.77 kg ha^{-1} for phosphorous, potassium and sulphur. These estimates of the canola production function model indicate P, K and S all are important factors in canola yield which has been previously found in agronomic research on the Canadian prairies. Liu, Gan, and Poppy (2014) conducted an on-farm study in western Canada and found that canola receiving potassium fertilizer increased seed yield relative to no potassium fertilizer applied. This same study found that with each 1 kg increase in S fertilizer, there was a corresponding increase in seed yield by 19 kg/ha, with applications in the 15-30 kg/ha range for sulphur appearing adequate to prevent it from being a limiting nutrient for canola (Liu, Gan, & Poppy, 2014).

5.4.2 Variety Index

The average marginal effect of the variety index is 5.01 as shown in Table 5-5, which indicates that for every 1% increase in the variety index (average sample yield of the variety relative to the average sample yield of L252) the yield of canola is estimated to increase by 5.02 kg ha^{-1}. The average yield in the data set for the check variety L252 was 2542 kg ha^{-1}. In the case of a producer who chooses to grow the canola variety L233P, which is 107.5% of the check variety of L252 (see Appendix A), the model estimates a 37.65 kg ha^{-1} canola yield increase relative to a producer who grows the canola variety L252.

5.4.3 Herbicide System

The estimated average marginal effect of the Liberty Link herbicide system relative to the Clearfield herbicide system is 71.2 kg ha^{-1} ($p < 0.001$). The estimated average marginal effect of Roundup Ready herbicide system relative to Clearfield herbicide system is 22.2 kg ha^{-1} ($p < 0.1$). These estimates support the previous findings of Liu , Gan and Poppy (2014) which found that cultivars with the Liberty Link herbicide system were the highest yielding on aggregate, with a

700 kg ha^{-1} increase in yield relative to Round-up Ready system (Liu, Gan, & Poppy, 2014). The herbicide-tolerance trait of canola varieties has been used to reduce weed pressure which can significantly increase yields (Harker, Blackshaw, Kirkland, et al., 2000; Harker, O'Donovan, Clayton, et al., 2008; Clayton, Harker, O'Donovan, et al., 2002). One hypothesis that explains these results is that Liberty Link herbicide systems have resulted in greater reductions in weed pressure relative to Roundup Ready and Clearfield herbicide systems, and thus have increased canola yields. Herbicide system was also interacted with variety index, which is further discussed in section 5.4.4.

5.4.4 Interaction Variety Index by Herbicide System

Interactions between variety index and herbicide were included in the model with statistically significant results. Canola grown with a Liberty Link herbicide system has a significantly ($p < 0.01$) lower yield response to the variety index relative to canola grown with a Clearfield herbicide system holding all else constant. Similarly, canola grown with a Roundup Ready herbicide system has a significantly ($p < 0.01$) lower yield response to the variety index relative to canola grown with a Clearfield herbicide system holding all else constant.

5.4.5 Average Historical Growing Season Precipitation and Growing Season Precipitation

The estimated average marginal effects of the 3-year average historical growing season precipitation on canola yield is 0.37 kg ha^{-1} ($p <0.01$) as shown in Table 5-5. The average historical growing season precipitation is used as a proxy for soil moisture. The results indicate that for every 1mm increase in historical growing season precipitation, the resulting increase in yield is 0.37 kg ha^{-1}. The squared term for average historical growing season precipitation is estimated to be negative with a value of -0.00272 ($p<0.1$) as shown in Table 5-6, indicating a diminishing marginal returns relationship between yield and historical growing season. Average historical growing season precipitation contributes positively to canola yield up to a point, while after that point negative effects on canola yield occur from increased average historical growing season precipitation. Assuming average historical growing season is a good proxy for soil moisture, it can by hypothesized that limited or excessive soil moisture can reduce crop yields.

The estimated average marginal effect of growing season precipitation on canola yield is -0.15 kg ha^{-1} but is not statistically significant as shown in Table 5-5. The squared term for growing season precipitation is estimated to be negative with a value of −0.00128 ($p<0.01$) as shown in Table 5-5, indicating a diminishing marginal returns relationship between yield and growing season precipitation. Similar to average historical growing season precipitation, the results indicate that growing season precipitation contributes positively to canola yield up to a point, while after that point negative effects on canola yield occur from increased growing season precipitation. The estimated effects of the 3-year average historical growing season precipitation and growing season precipitation support the agronomic theory that excessive or limited precipitation can lead to reduced crop yields. Extreme values for soil moisture and in-season precipitation may result in reduced crop yields by the way of reduced plant growth, increased disease pressure and reducing plant available nutrients (Franklin, Kav, Nate, et al., 2005; Bedard-Haughn, 2009).

5.4.6 Seeding date

The average marginal effects of seeding date (days after May 14) on canola yield is -2.50 ($p<0.01$). This indicates that for every additional day delay in seeding past May 14, canola yield decreases by 2.50 kg ha^{-1}. This is in line with previous literature, as delayed seeding beyond May 15 has been found to reduce canola yield as this can increase the incidence of fall frost and aborted flowers due to heat stress (Catellier, 2022). The squared term for seeding date was estimated to be −0.376 ($p<0.001$) which indicates a diminishing marginal returns relationship between yield and seeding date. This supports the previous agronomic literature on the impact of seeding date on yield with extreme values generally resulting in lower yields.

5.4.7 Fungicide

The model estimates that fungicide application in-season has a large and significant impact on canola yield. The model estimates that a fungicide application increases canola yield by 152 kg ha^{-1} ($p<0.001$) relative to no fungicide application. This supports the previous findings that fungicide applications can increase yield especially in the incidence of high disease pressure (Kutcher & Wolf, 2006) but even in years with minor incidence of disease (Harker, et al., 2011).

5.4.8 Previous crop

The average marginal effect of previous crop cereal on canola yield is not significant when compared to that of previous crop oilseed. However, the average marginal effect of previous crop pulse on canola yield is significant when compared to that of oilseed. Canola grown on previous crop pulse is estimated in the model to have an average marginal effect of 11.29 kg ha^{-1} ($p<0.1$) on canola yield relative to oilseed previous crop. Crop rotations with pulse crops have previously been found to positively impact canola yield. Nitrogen fixing legumes such as field peas have been found to boost canola yields compared to non-legumes such as cereals (O'Donovan, et al., 2014). Pulse crops fix their own nitrogen which may result in increased nitrogen soil reserves, which may boost canola yields the following year. Other rotational benefits of pulse crops have been found in literature including higher residual soil moisture (Elliot, Papendick, & Bezdicek, 1987), more rapid N mineralization in residues of higher N concentration (Janzen & Kucey, 1988; Sandford & Hairston, 1984), a loose, mellow soil surface (Moldenhauer, et al., 1983) and a lower C:N ratio in soil organic matter (Hargrove, 1986). The previous crop variable was also interacted with nitrogen, which is further discussed below in section 4.4.9.

5.4.9 Nitrogen

The overall average marginal effect of nitrogen on canola yield is 2.84. This indicates that a 1 kg ha^{-1} increase in the amount of applied nitrogen will increase canola yield by 2.82 kg ha^{-1}, holding all else equal. The coefficient on the squared nitrogen term is estimated to be negative with a value of -0.0140 ($p<0.01$), indicating a diminishing marginal returns relationship between yield and nitrogen. Nitrogen contributes positively to canola yield up to a point, while after that point negative effects on canola yield occur. In the model, nitrogen is interacted with previous crop and variety index. The results of nitrogen response by previous crop and variety are discussed below in section 5.4.9.1 and 5.4.9.2.

5.4.9.1 Nitrogen Conditioned on Previous Crop

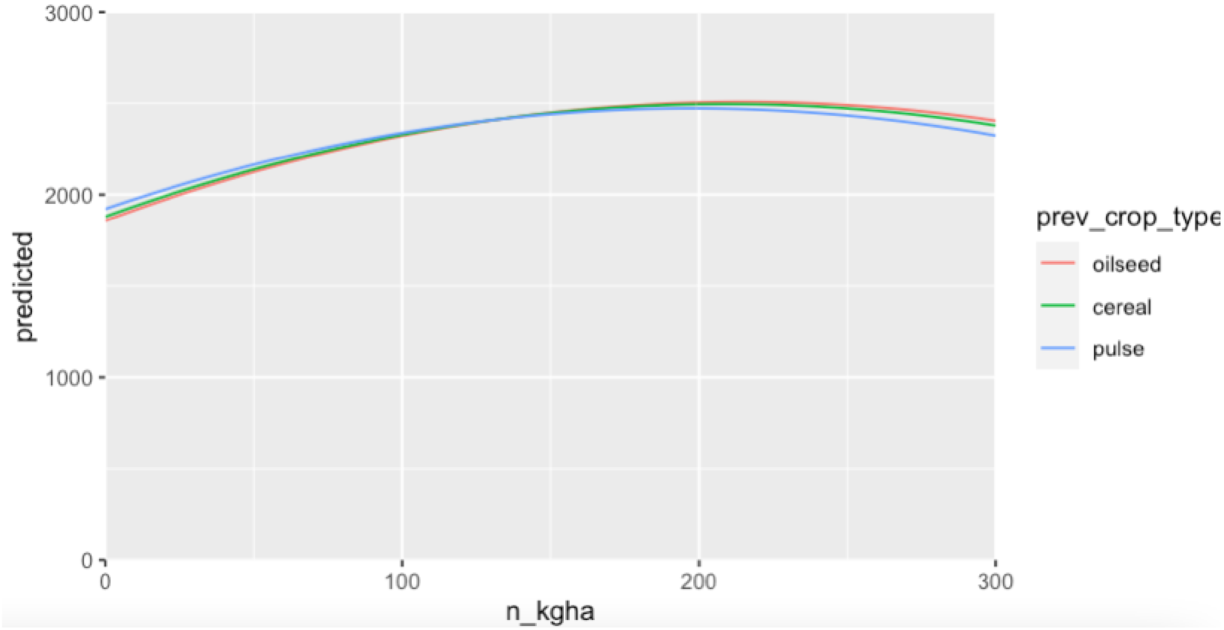
The canola yield response to nitrogen was conditioned on previous crop, with the reference category being oilseed. Canola grown on fields with previous crop pulse had a significantly lower yield response to applied nitrogen relative to oilseed previous crop ($p<0.1$). There was no statistical difference between the canola yield response to nitrogen on previous crop cereal when compared to the canola yield response to nitrogen on previous crop oilseed. When considering nitrogen use of the previous crop, these results are perhaps unsurprising. The primary crop in the oilseed category is canola, which is a high nitrogen use crop (Government of Saskatchewan, 2022). Therefore, canola grown on fields previously cropped to canola may have more depleted nitrogen soil reserves as compared to canola gown on fields previously cropped to a pulse which fixes its own nitrogen. These estimates indicate that when planting a canola crop on a field that was previously planted to a pulse crop, the applied nitrogen fertilizer response curve for canola is lower than canola grown on a field that was previously planted to an oilseed crop.

Figure 5-3 shows the average adjusted predicted canola yield in response to nitrogen by previous crop. The model yield predictions are based on a range of nitrogen rates from 0 -300 kg ha^{-1} while all other variables are at the means or modes as specified in Table 5-3. From Figure 5-3, the nitrogen response of canola on pulse previous crop reaches the maximum yield at a lower nitrogen rate when compared to the nitrogen response of canola on previous crop oilseed. Additionally, the canola yield is highest on previous crop pulse when nitrogen is applied at low rates, relative to previous crop oilseed. As previously mentioned, one possible explanation for these results is that as pulse crops fix nitrogen, canola grown the following year will require less nitrogen due to higher soil nitrogen reserves. However, this is a hypothesis only as this study does not account for soil residual nitrogen and only has data on applied nitrogen.

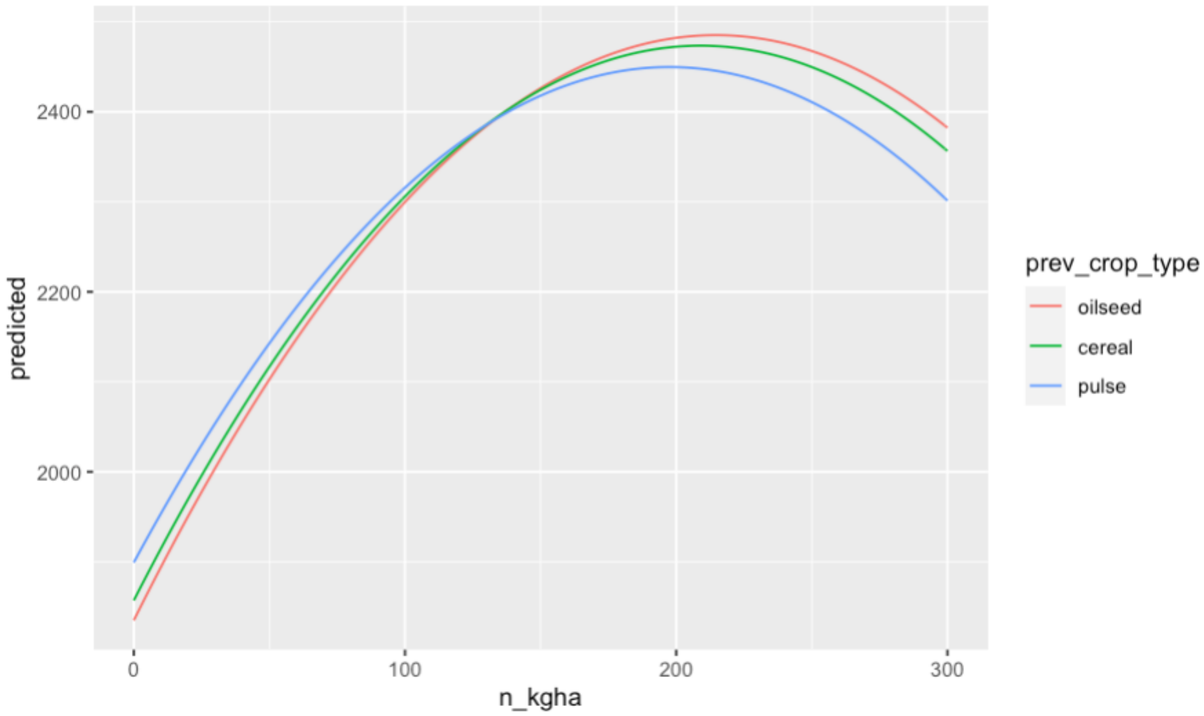
Figure 5-3 Average adjusted predicted canola yield in response to N by previous crop.

Predicted canola yield based on range of nitrogen rates and the means and modes of variables outlined in Table 5-3. Panel A is the full graph. Panel B is zoomed in graph for clarity.

Panel A



Panel B



5.4.9.2 Nitrogen Conditioned on Variety Index

The coefficient estimated on the interaction of nitrogen with variety index is positive and significant ($p<0.01$). The positive sign of this interaction indicates that as the variety index (average yield of chosen variety in the sample relative to the average yield of L252 in the sample) increases, the canola yield response to nitrogen also increases. This result indicates that higher yielding varieties require higher rates of nitrogen. This result is in line with nutrient guidelines for canola on the prairies, with higher canola yields increasing the total nitrogen uptake and removal (Canadian Fertilizer Institute, 2021).

5.4.9.3 Marginal Product of Nitrogen by Previous Crop and Year

Since the marginal effect of nitrogen is of particular importance for this project, the average marginal effect (AME) of nitrogen by previous crop and year are shown in Table 5-7. The AME estimates the partial effect of nitrogen on canola yield using every observed value of the other covariates then averages across the resulting effect estimates. The average marginal effects across previous crops and over the years 2011-2019 ranges from 2.32 (previous crop pulse in 2013) to 3.11 (previous crop oilseed in 2019). Between previous crop types, the lowest average marginal effect occurs in pulse previous crop, with the highest average marginal effect occurring in oilseed previous crop. Across the years 2011-2019, the lowest average marginal effect of nitrogen occurred in 2011 while the highest average marginal effect of nitrogen occurred in 2019. Due to the lack of large variation in the AME across years within each previous crop type, a simple rule was used to calculate the EONR across all years for each crop type (equations 5-4, 5-5, and 5-6).

Table 5-7 Average Marginal Effect (AME) of nitrogen within previous crop and year.

Previous crop	Year	Estimate	st. error
cereal	2011	2.71***	0.48
oilseed	2011	2.86***	0.49
pulse	2011	2.37***	0.51
cereal	2012	2.72***	0.47
oilseed	2012	2.88***	0.48
pulse	2012	2.38***	0.52
cereal	2013	2.73***	0.44
oilseed	2013	2.80***	0.45
pulse	2013	2.32***	0.48
cereal	2014	2.81***	0.44
oilseed	2014	2.91***	0.44
pulse	2014	2.39***	0.47
cereal	2015	2.84***	0.42
oilseed	2015	3.06***	0.45
pulse	2015	2.54***	0.47
cereal	2016	2.88***	0.42
oilseed	2016	3.02***	0.44
pulse	2016	2.60***	0.47
cereal	2017	2.9***	0.42
oilseed	2017	2.96***	0.43
pulse	2017	2.61***	0.47
cereal	2018	2.92***	0.43
oilseed	2018	3.05***	0.45
pulse	2018	2.71***	0.48
cereal	2019	2.99***	0.44
oilseed	2019	3.11***	0.46
pulse	2019	2.72***	0.49

5.5 Economically Optimal Fertilizer Use

The estimated marginal product of nitrogen from the canola production function estimates is used to estimate the economically optimal nitrogen application rate (EONR) for Saskatchewan canola. As described in section 3.2.6, the first order conditions for maximization of expected profit (E[π]) states that the expected output price of canola (E[p_{it}]) multiplied by the marginal product of nitrogen (MP_N) should equal the input price of canola. The EONR is where the MP_N is equal to the expected cost ratio (E$[CR_t]$), where the cost ratio is the price of nitrogen (w_{itN}) relative to the expected price of canola (E$[p_{it}]$) as described in equation 3-8. Saskatchewan producers may incur very difference nitrogen prices and may also have very different expectations about canola prices when making planting decisions. Therefore, individual producers may have very different economic optimums for nitrogen fertilizer use in canola. A few reasons for differing prices include differing transportation costs, storage capabilities, use of different fertilizer forms (dry, liquid, vs. anhydrous), time of selling/purchase. Acknowledging the range of different prices faced by producers, this section includes the calculation of the EONR at a range of cost ratios in order to provide insight for different scenarios.

5.5.1 Equations for Economic Optimum Nitrogen Rate

The marginal product of nitrogen that is derived from the canola production function is conditional on the previous crop and variety index of the variety grown as shown in equation 5-3. This is due to nitrogen being interacted with previous crop and variety index in the production function. This is described in equations 5-4, 5-5, and 5-6 which calculate the estimated optimal nitrogen rate specific to the previous crop and variety index. The relevant coefficients required for these equations are shown in Table 5-8. These equations require a value for variety index of the chosen variety. For reference, see Appendix A for a list variety index values for the varieties included in the dataset. If producers wish to use these formulas to calculate their own estimated optimal nitrogen rate, these formulas can be used by entering their own cost ratios, previous crop, and variety index.

5-3

$$\mathrm{E}[CR_t] = \mathrm{E}[MP_{N_{it}}]$$

$$\mathrm{E}[CR_t] = b18 + 2 * b19 * N_{it} + b20 * Cereal_{i(t-1)} + b21 * Pulse_{i(t-1)} + \ b22 * \ Variety\ Index_{it}$$

5-4

$$EONR_{Oilseed\ Previous\ Crop} = \frac{(b18 + b22 * Variety\ Index_{it} - \mathbf{E}[CR_t])}{-2 * b19}$$

5-5

$$EONR_{Cereal\ Previous\ Crop} = \frac{(b18 + b20 + b22 * Variety\ Index_{it}\ - \mathbf{E}[CR_t])}{-2 * b19}$$

5-6

$$EONR_{Pulse\ Previous\ Crop} = \frac{(b18 + b21 + b22 * Variety\ Index_{it}\ - \mathbf{E}[CR_t])}{-2 * b19}$$

Table 5-8 Required coefficients for estimated optimal nitrogen calculation.

Coefficient Name	Coefficient Number	Estimates
N	b18	1.86
N^2	b19	-0.0140
N x Cereal Previous crop	b20	-0.155
N x Pulse Previous crop	b21	-0.482
N x Variety Index	b22	0.0444

5.5.2 Economic Optimal N for Average Annual CR

Using the historical annual cost ratios of nitrogen to canola outlined in Figure 4-2, the estimated economic optimal nitrogen application rate is calculated for a range of price scenarios. Table 5-9 shows the EONR by previous crop using the average cost ratio for each individual year from 2011-2019. When comparing the EONR between previous crops, the estimated optimal nitrogen rate was highest for oilseed previous crop and lowest for pulse previous crop for any given cost ratio.

Table 5-9 Estimated optimal nitrogen application rate by previous crop and annual average cost ratios with variety index at the annual mean.

Year	Canola Price ($/ tonne)	N Cost ($/tonne)	Mean Variety Index (% of L252)	Cost Ratio	EONR (kg ha^{-1})	St. Error	Obs. Mean N Rate (kg/ha)
Oilseed Previous crop							
2011	$478	1158	83.5	2.42	113	15.6	98
2012	$461	1390	84.3	3.02	92.6	18.2	99
2013	$529	1352	87.1	2.56	114	15.2	104
2014	$432	1287	90.1	2.98	103	16.1	107
2015	$418	1309	93.2	3.13	103	16.3	106
2016	$446	1195	95.6	2.68	123	15.1	111
2017	$466	1061	97.6	2.27	141	17.1	117*
2018	$501	1035	101.6	2.07	154	20.3	120*
2019	$511	1208	103.9	2.36	147	19.1	121*
Cereal Previous crop							
2011	$478	1158	83.5	2.42	107	15.5	97
2012	$461	1390	84.3	3.02	87	19.0	99
2013	$529	1352	87.1	2.56	108	15.0	103
2014	$432	1287	90.1	2.98	97.7	16.6	104
2015	$418	1309	93.2	3.13	97.2	16.8	108
2016	$446	1195	95.6	2.68	117	14.5	111*
2017	$466	1061	97.6	2.27	135	15.6	113*
2018	$501	1035	101.6	2.07	149	18.4	118*
2019	$511	1208	103.9	2.36	142	17.5	119*
Pulse previous crop							
2011	$478	1158	83.5	2.42	95.5	18.8	100
2012	$461	1390	84.3	3.02	75.3	23.5	98
2013	$529	1352	87.1	2.56	96.2	18.5	106
2014	$432	1287	90.1	2.98	86.0	20.7	108*
2015	$418	1309	93.2	3.13	85.5	21.0	108*
2016	$446	1195	95.6	2.68	105	17.2	110
2017	$466	1061	97.6	2.27	123	16.3	112
2018	$501	1035	101.6	2.07	137	17.7	116*
2019	$511	1208	103.9	2.36	130	17.5	118*

*indicates that the observed mean rate is outside of the EONR st.errors

5.5.3 Observed vs. Optimal Nitrogen Rates by Year and Previous crop

Over the years 2011-2019 the observed mean nitrogen application rate in the data sample is trending upwards. This indicates that producers are continuing to increase the rate of nitrogen applied on average year over year, regardless of the average annual cost ratio. The time trend of increasing nitrogen application by Saskatchewan producers indicates that the fertilizer application rates in canola are still evolving as the producer nitrogen application rate is trending upwards. One potential explanation for this is that producers are still discovering the economic optimal nitrogen rate for canola. Nitrogen fertilizer application rates may be increasing based on agronomic recommendations, which are typically based on target yields. There could be several underlying factors that are causing agronomists and producers to aim for higher canola yields. One such factor may be the increasing yield potential of canola varieties that are grown by producers over time. This is captured in the average variety index over the years 2011 – 2019 within the data sample. In the average variety index of the variety chosen by producers in 2011 was 83.5% which increases to 103.9% in 2019. Within the data, the variety index on average shows a strong upward trend over the years 2011-2019. Another potential reason for nitrogen fertilizer rates increasing over the period 2011-2019 is increasing adoption of higher capacity equipment that allows for higher nitrogen rates to be applied with greater ease. The increasing rates of nitrogen applied by Saskatchewan producers observed in the sample may be a combination of these factors.

The estimated optimal nitrogen rate in the model is conditional on previous crop and the variety index of the variety chosen by producers. Due to the estimated value of the coefficients in the crop production model for the interactions of nitrogen with previous crop type and variety index, the EONR for previous crop pulse crops are lower than those for previous crop cereal and oilseed while the EONR increases with increasing values for variety index. The annual average variety index in the data is used to estimate the annual EONR for each oilseed, cereal, and pulse previous crops at the average annual cost ratio. For previous crop oilseed and cereal producers are observed on average to be applying nitrogen within the range of standard errors of the EONR over the years 2011-2016. In the years 2017-2019 producers on average were under-applying nitrogen in comparison to the EONR. For previous crop pulse, producers on average appear to be applying nitrogen within the range of standard errors of the EONR over the years 2011-2013, 2016 and 2017. In the years 2014 and 2015 producers appear on average to be applying nitrogen above the range of standard errors of the EONR. Conversely, in the years 2018 and 2019 producers appear on average to be applying nitrogen below the range of standard errors of the EONR. Across all previous crop types, in nearly all years on average producers are observed to be applying nitrogen at rates that are below or near the EONR.

5.5.4 Robustness Check: Observed vs. Optimal Nitrogen Rates by Year and Previous crop Results from an Alternative Model

The chosen canola production function model included year x producer fixed effects. A robustness check is included due to the potential issue of endogeneity in the source of variation of nitrogen rates across fields within years by producers as described in section 5.2.4.2. A comparison between the EONR estimates of an alternative model with risk zone x year is discussed in relation to the estimates of the chosen model which instead included year x producer fixed effects. The alterative estimated optimal nitrogen rates by year and previous crop from a model with risk zone x year fixed effects (Model 6 in Table 5-3) can be found in Appendix B in Table B.3. One difference between the alternative and chosen model was the significance of the previous crop type x nitrogen interactions. In the alternative model, the estimates indicated no statistical difference between the EONR estimated for each previous crop type while the chosen model estimated a statistical difference between the nitrogen response conditional on previous crop type (+ $p < 0.1$). Another difference between models is that the standard errors of the alternative model are smaller than those of the chosen model. The EONR at lower variety indexed vales using the alternative model are significantly lower than those estimated in the chosen model. In this alternative model, estimated optimal applied nitrogen rates range from 42-154 kg N/ha as shown in Table B.3. Several of the estimated optimal nitrogen rates in the alternative model seem quite low relative to the recommended rates. Using the 2012 average cost ratio and the variety index of 84%, the estimated optimal is 42 kg N/ha for previous crop type pulse. Very few producers in the sample are applying nitrogen at these low rates and this estimated EONR is below the recommended agronomic nitrogen rates for Saskatchewan in the 2012 crop planning guide which ranged from (70-80 kg N ha^{-1}) (Saskatchewan Ministry of Agriculture, 2022).

The divergence between the alternative and chosen model EONRs is mainly in the estimation at lower variety index values. However, at the mean variety index values observed in

2017-2019 (97.6, 101.6, 103.9) the EONR estimates of the alternative model are within the range of the chosen model standard error. Similarly, the EONR based on the alternative model from 2017-2019 across all previous crop types is within the range of the EONR of the chosen model. When comparing the EONR of the alternative model to the observed annual nitrogen rates in the sample using average annual prices of canola and nitrogen, the estimates suggest that producers on average are over-applying nitrogen from the years 2011-2015 at lower variety index values and under-applying nitrogen over the years 2017-2019 at higher variety index values across all previous crop types. This differs from the estimates of the chosen model, which suggests that producers have often applied sub-optimal rates over the years 2011-2015 but have since been under-applying on average relative to the estimated EONR over the years 2017-2019. The chosen and alternative model differ based on the inclusion of fixed effects and result in different EONRs at low variety index values. However, the EONR utilized in the environmental policy simulations is based on the 2019 average annual cost ratio and observed mean variety index in 2019 (103.9%). While the 2019 EONR from the chosen model is lower than that estimated in the alternative model, the alternative model estimates are still within the chosen model standard errors.

5.5.5 Economic Optimal N for Range of CR

A range of EONR were calculated using the mean 2019 variety index value (103.9% of L252) for the three different previous crops based on a range of different price ratios in Table 5-10. Different combinations of nitrogen prices and expected canola prices result in very different estimated optimal nitrogen rates. When using different combinations of expected canola prices ranging from$ 400-700 t^{-1} and \$1000 – 1700 t^{-1} the optimal nitrogen rate calculated for oilseed previous crop ranges from 79.7 – 181 kg ha^{-1}. While for cereal previous crop the EONR ranges from 74.2 – 175 kg ha^{-1} and for pulse previous crop the EONR ranges from 62.5 – 163 kg ha^{-1}. A version of Table 5-10 with an alternative variety index of 93.3% can be found in Table B.6.

Table 5-10 Estimated optimal nitrogen rate by previous crop and a range of canola prices and nitrogen costs using the mean variety index of 2019 (103.9% of L252).

			Oilseed Previous crop		**Cereal Previous crop**		**Pulse Previous crop**	
Canola Price ($ t^{-1})	**N Cost ($$t^{-1}$)**	**Cost Ratio**	**EONR (kgha^{-1})**	**St. Error**	**EONR (kgha^{-1})**	**St. Error**	**EONR (kgha^{-1})**	**St. Error**
$ 400	$ 1,000	2.50	142	18.2	137	16.7	125	17.3
$ 400	$ 1,250	3.13	120	16.4	114	16.1	103	19.1
$ 400	$ 1,500	3.75	97.6	18.9	92.1	19.7	80.4	24.0
$ 400	$ 1,700	4.25	79.7	23.1	74.2	24.5	62.5	29.2
$ 500	$ 1,000	2.00	160	22.0	155	20.1	143	18.9
$ 500	$ 1,250	2.50	142	18.2	137	16.7	125	17.3
$ 500	$ 1,500	3.00	124	16.4	119	15.9	107	18.4
$ 500	$ 1,700	3.40	110	17.0	105	17.3	92.9	20.9
$ 600	$ 1,000	1.67	172	25.3	166	23.1	155	21.1
$ 600	$ 1,250	2.08	157	21.3	152	19.4	140	18.5
$ 600	$ 1,500	2.50	142	18.2	137	16.7	125	17.3
$ 600	$ 1,700	2.83	131	16.7	125	15.8	113	17.7
$ 700	$ 1,000	1.43	181	27.9	175	25.7	163	23.2
$ 700	$ 1,250	1.79	168	24.1	162	22.0	150	20.2
$ 700	$ 1,500	2.14	155	20.8	150	18.9	138	18.2
$ 700	$ 1,700	2.43	145	18.6	139	17.1	128	17.8

5.5.6 Economic Optimal N for a Range of Variety Indices

Since the marginal product of nitrogen is conditioned on variety index, Table 5-11 shows the estimated optimal nitrogen rate by previous crop and by a variety index ranging from 90 – 110 % of the average yield of the check variety of L252. The estimated optimal nitrogen rate increases significantly when a canola variety with a higher variety index is grown. These results indicate that for higher yielding varieties more nitrogen is required across all previous crop types. The highest optimal rate within this range of variety index occurs on oilseed previous crop with 110% variety index, where the EONR is 157 kg ha^{-1} $\pm$ 21.80. These results suggest that as producers over time adopt higher yielding canola varieties, the optimal rate of nitrogen will correspondingly increase.

Table 5-11 Estimated optimal nitrogen rate by previous crop using the 2019 average cost ratio at differing the variety index values of 90, 93.3, 100, 103.9 and 110% (93.3% is the mean value for variety index in the data over the years 2011-2019, 103.9% is the mean value for the variety index in 2019).

Previous crop	Variety Index (% of L252 avg. yield)	Canola Price ($/ tonne)	N Cost ($/tonne)	Cost Ratio	EONR (kg ha^{-1})	St. Error
Oilseed	90	511	1208	2.36	126	15.0
	93.3	511	1208	2.36	131	15.4
	100	511	1208	2.36	142	17.2
	103.9	511	1208	2.36	147	19.1
	110	511	1208	2.36	157	21.8
Cereal	90	511	1208	2.36	120	14.2
	93.3	511	1208	2.36	125	14.3
	100	511	1208	2.36	136	15.7
	103.9	511	1208	2.36	142	17.5
	110	511	1208	2.36	151	20.1
Pulse	90	511	1208	2.36	109	16.5
	93.3	511	1208	2.36	114	16.1
	100	511	1208	2.36	124	16.5
	103.9	511	1208	2.36	130	17.5
	110	511	1208	2.36	140	19.4

5.5.7 Discussion of Economic Optimal Nitrogen Estimates

In the calculation of the EONR, a range of expected canola prices, nitrogen costs, variety index values, and previous crop types were utilized. Expected canola prices of $400 – 700/tonne of canola and a range of nitrogen fertilizer costs from $1000 – 1700/tonne of N were used in the economic analysis. As the production function model is conditioned on previous crop and variety index, a range of variety index values from 83.5-110% were used in the EONR calculations as well as previous crops of pulse, oilseed, and cereal. The estimated optimal nitrogen application rate ranges from 62.5 - 181 kg ha^{-1}. This range of calculated economic optimal nitrogen application rates is similar to those calculated in previous research. In previous small plot studies conducted by Mahli et al. (2007) on canola in Saskatchewan, the economic optimum nitrogen fertilizer application rate ranged from 106-167 kg ha^{-1} under moist conditions and 66-105 kg ha^{-1} under drier conditions. The economic optimum calculations in this small plot study were conducted using a range of canola prices from \$200-400 t^{-1} and fertilizer costs ranging from \$500-1000 t^{-1} of N (Mahli et al., 2007).

Using the annual average prices for 2019 and the average variety index over the years 2011-2019 (93.3%) the estimated ENOR was 114, 125 and 131 kg N ha^{-1} for previous crop pulse, cereal oilseed respectively. The Saskatchewan Crop Planning Guide in 2019 used the nitrogen fertilizer rates of 124, 121, 114 kg ha^{-1} for the black, dark brown and brown soil zones respectively (Saskatchewan Ministry of Agriculture, 2022). This suggests that the estimated EONR is within the same range as those provided in the Saskatchewan Crop Planning Guide. However, when estimating the EONR using the average variety index of 2019 (103.9%) the estimated ENORs were 130, 142 and 147 kg N ha^{-1} for previous crop pulse, cereal oilseed respectively. At this higher variety index value, the estimated EONRs are higher than those recommended in the Saskatchewan Crop Planning Guide.

The results indicate that on average producers are not on average over-applying nitrogen in canola in reference to the estimated EONR. However, there are many different reasons why producers may not be applying nitrogen at the estimated economic optimal nitrogen rates. Firstly, producers may in fact have a wide range of differing economic optimal nitrogen rates. It is important to note that this analysis is limited to using average annual cost information for canola and nitrogen prices. Relative to the average annual price, Saskatchewan producers may incur very difference nitrogen prices and may also have very different expectations about canola prices when making planting decisions. Therefore, individual producers may have very different economic optimums for nitrogen fertilizer use in canola. Secondly, there are a wide variety of reasons that canola growers may not apply nitrogen at the economically optimal rate including perceptions of risk, target yields, access to credit and seeding equipment capacity. Nitrogen rates applied by Saskatchewan canola growers may not be at the ENOR as fertilizer decisions incorporate the producers' perceptions of risk such as expectations of growing season conditions, target yields and unexpected changes in the sale price of canola. In considering the EONR, it is important to note that current agronomic nitrogen recommendations for canola depend on target yields. According to the Canola Council of Canada, Canola needs 2.8 - 4 kg ha^{-}

^{1} of available nitrogen per 56 kg of seed yield (Canola Council of Canada, 2020). Canola growers may set lower target nitrogen fertilizer levels as a means of managing risk (Mahli, et al., 2007). The guidelines for required nitrogen per kg of canola seed yield ranges from 0.058 – 0.07 kg of N kg^{-1} of canola seed (Canadian Fertilizer Institute, 2021). Based on these guidelines, at the highest estimated EONR of 181 kg of N ha^{-1}, the target yield of canola would be 2586 - 3121 kg ha^{-1}. For the 2019 average annual cost ratio on cereal previous crop with variety index of 103.9%, 142 kg ha^{-1} was the calculated as the optimal nitrogen application rate. The target yield of canola using these guidelines for 142 kg ha^{-1} would be 2028 – 2448 kg ha^{-1}. Another factor that may greatly impact producer fertilizer decisions is access to credit, as limited credit may result in rates below the EONR (Mahli, et al., 2007). Another potential reason why producers may apply nitrogen at rates below the EONR include time, capacity and equipment constraints at seeding time which limit the ability to apply high nitrogen rates. In the case of producers who apply most of their nitrogen at seeding time, due to the limited seeding window for producers in Saskatchewan, there is a time and logistical constraint that producers must weigh. Operator error and mechanical failures may be other factors that result in applied nitrogen rates that stray from the EONR. As shown in the estimated canola production function model, the seeding date of canola is an important determinant of canola yield. The estimated canola production function in this thesis and previous agronomic literature has found evidence that at extreme seeding dates (too early or too late) canola yield loss can occur. Delayed seeding beyond May 15 has been found to reduce canola yield as this can increase the incidence of fall frost and aborted flowers due to heat stress (Catellier, 2022). Applying more nitrogen at planting can significantly increase the time required to complete seeding. Therefore, the economically optimal nitrogen rate based solely on the input price may be an underestimation of the true cost of applying nitrogen. In summary, the nitrogen fertilizer decisions made by producers are greatly impacted by many factors including the input output cost ratio, perceptions of risk, target yields access to credit, capacity of seeding equipment and target yields.

5.6 Summary

This concludes the chapter on the estimation process, regression results and estimated optimal nitrogen application rates. The estimation process included a description of the data analysis, model specification, and specification testing. The development of the production function model was based on relevant agronomic theory and previous econometrics models. A discussion of the estimation process including inclusion of interactions and fixed effects is provided followed by testing for homoskedasticity. A comparison of the residuals vs. predicted values of the chosen model were also provided. The regression results were presented with particular emphasis on the crop yield response to nitrogen as this is a major focus of this thesis. The optimal nitrogen use estimates include results for various price scenarios, previous crops, and variety index. The observed vs. estimated optimal nitrogen rates by year, previous crop and variety index are also provided including a robustness check by considering the EONR of an alternative model. This was followed by a discussion of the EONR results. The next chapter will use the EONR results described in this chapter to assess environmental policy scenarios regarding nitrogen use.

CHAPTER 6 ENVIRONMENTAL POLICY SCENARIO RESULTS

6.1 Introduction

As the Government of Canada has set targets for reduced GHG emission from nitrogen fertilizer of 30% by the year 2030 from 2020 levels, the objective of this section was to explore whether a 30% reduction in emissions through reduced fertilizer use aligns with the government's own carbon pricing levels. This chapter considers two avenues of N_2O abatement from nitrogen fertilizer application: 1) Nitrogen fertilizer application reduction 2) Tax on N_2O Emissions using the Government of Canada's social cost of carbon.

These two scenarios were assessed using the estimated farm level nitrogen fertilizer yield response functions shown in Table 5-6. The estimates for direct N_2O emissions from nitrogen application used in this analysis were sourced from a study which was the basis of Environment and Climate Change Canada's estimates in the 2018 National Inventory Report: greenhouse gas sources and sinks in Canada (Environment and Climate Change Canada, 2018; Rochette, et al., 2018; Rochette, et al., 2008) . The emissions factors used to calculate direct GHG emissions associated with nitrogen application in the black and brown soil zone are outlined in Table 3-2. As previously noted in Section 3.4.3, for the purposes of this thesis the direct GHG emissions associated with nitrogen application were the only GHG emissions considered, as indirect emissions from nitrogen application were not taken into account. The calculations of net return and GHG mitigation cost from reduced nitrogen fertilizer application were described in equations 3-14 and 3-15 respectively. The calculations for the tax on N_2O emissions scenario including economic optimum, net return and GHG reduction are shown in equations 3-16, 3-17 and 3-18. Current and future social costs of carbon by the Government of Canada are outlined as shown in Table 3-3 (Government of Canada, 2022). The annual average prices of canola and nitrogen from 2019 were used throughout both scenarios.

In the first section of this chapter, the nitrogen fertilizer application reduction scenario is considered. Under conditions of reduced nitrogen fertilizer application yield and net return penalties, economic response, and marginal costs of GHG mitigation are estimated. The second part of this chapter includes results of a scenario where a tax on N_2O emissions using the Government of Canada's social cost of carbon is applied. Under a tax on N_2O emissions, the post-tax economic optimum, yield and net return penalty and GHG reduction are estimated. A comparison of a 30% nitrogen fertilizer reduction with a tax on N_2O emissions using the Government of Canada's social cost of carbon is examined including a comparison of the welfare effects. Finally, a discussion of the results from the nitrogen fertilizer application reduction scenario, tax on N_2O emissions and the comparison of a 30% nitrogen fertilizer reduction with a tax on N_2O emissions is provided.

6.2 Nitrogen Fertilizer Application Reduction Scenario

6.2.1 Yield and Net Return Penalties from Reduced Nitrogen Application from EONR

The yield and net revenue (NR) penalty estimates are based on a reduction in N applied ranging from 20 – 60 kg ha^{-1} from the estimated economic optimum nitrogen rate. The EONR estimate is based on annual average prices in 2019 (\$511 t^{-1} canola and \$1208 t^{-1} nitrogen) as well as the average variety index in 2019 (103.9%). The yield penalties and reduction in net return due to nitrogen fertilizer reduction from the calculated economic optimum were estimated for canola grown on previous crop oilseed, cereal and pulse as shown in Table 6-1. The yield penalties were nearly identical across previous crop type, with a 20 kg ha^{-1} reduction in nitrogen fertilizer applied corresponding to an estimated reduction in canola yield by 52.1 - 53.7 kg ha^{-1}. In order to gauge the scale of the yield penalties, the average adjusted predicted yields were estimated based on the specified economically optimal nitrogen rate and previous crop type, with all other categories set at their mean or mode. This predicted yield at the optimal nitrogen rates ranges from 2461 – 2504 kg ha^{-1}. At a reduction in nitrogen fertilizer applied by 20 kg ha^{-1}, the estimated reduction in canola yield by 53 kg ha^{-1} corresponds to a 2.09 - 2.15% yield penalty of the average adjusted predicted yield. Yield penalties increase corresponding to increasing reduced fertilizer application from the economic optimum. A reduction in nitrogen applied by 60 kg ha^{-1} results in a yield penalty of 191-193 kg ha^{-1}, which corresponds to a 7.67 - 7.81% yield penalty of the average adjusted predicted yield. The yield penalties from reduced rates of nitrogen fertilizer application have impacts on producer net return. Reduction in nitrogen fertilizer led to reduced net return, as the costs saved from reduced nitrogen use did not cover the losses incurred from the yield penalty. In the case of a 20 kg ha^{-1} reduction in nitrogen fertilizer applied, this results in an estimated reduction in net return of \$2.85 - 2.90 ha^{-1}. A reduction in nitrogen applied by 60 kg ha^{-1} results in larger producer net return loses of \$25.5 - 25.9 kg ha^{-1}.

Table 6-1 Yield and net revenue penalty estimates from reduced nitrogen application from the EONR which is based on annual average prices and variety index in 2019 (\$511 t^{-1} canola, \$1208 t^{-1} nitrogen, 103.9% of L252).

Economic Opt N (kg/ha)	**Avg. Adj. Pred.Yield at Opt. N** [2]	**Reduction N (kg/ha)**	**App N (kg / ha)**	**Estimated Yield Penalty**[3] **(kg/ha)**	**St. Errors**	**% Yield Penalty of Predicted Yield**	**NR Reduction (\$/ha)**
			Oilseed Previous crop				
		20	127	53.7	9.82	2.14	2.90
		40	107	118	18.6	4.71	11.6
147	2504(251.3)	60	87	193	27.9	7.72	25.9
			Cereal Previous crop				
		20	122	52.1	8.92	2.09	2.77
		40	102	116	17.6	4.66	11.3
142	2491(251.4)	60	82	191	27.5	7.67	25.5
			Pulse Previous crop				
		20	110	53.0	9.75	2.15	2.85
		40	90	117	20.3	4.75	11.4
130	2461(252.5)	60	70	192	33.0	7.81	25.7

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[2] Predicted yields for the economic optimums for each previous crop type were estimated. The predicted yields were derived using the 'predictions' function in the *MarginalEffects* package. The average adjusted predictions are reported based on the specified nitrogen rate, previous crop type and variety index and the mean(or mode) for all other categories The mean/mode for the reference categories used in making this predicted yield include: using an average canola yielding customer, risk zone 17, soil class G, year 2015, 32 phosphorous, 4 potassium, 22.8 sulphur.

[3] The estimates of yield penalty and the associated st.errors were derived using the 'deltamethod' function from the *MarginalEffects* package. The 'deltamethod' function was used to test the hypothesis of the difference between the marginal effect of nitrogen at the optimal and the marginal effect of nitrogen at a reduced nitrogen rate. For example, for oilseed previous crop the following hypothesis was tested to estimate the yield penalty from a reduced nitrogen rate: *((b1*Nitrogen_optimal) +(b2*Nitrogen_optimal ^2) + (b20*Nitrogen_optimal*VarietyIndex)) – ((b1*Nitrogen_reducedrate)+(b2*Nitrogen_reducedrate^2) + (b20*Nitrogen_reducedrate*variety_index_percent)) = 0)*

The Government of Canada has set targets for nitrogen fertilizer GHG emissions to be reduced from 2020 levels by 30% by the year 2030 (Government of Canada, 2022). Therefore, the effect of a reduction in nitrogen fertilizer use from the optimum by 30% is assessed in Table 6-2. The largest yield penalty estimated from an across-the-board reduction in nitrogen fertilizer use by 30% occurs on canola grown on oilseed previous crop (132 ± 20.4 kg ha^{-1}). This yield penalty corresponds to 5.29% of the average adjusted predicted yield for previous crop oilseed. The smallest yield penalty estimated from a 30% reduction in nitrogen fertilizer use from the optimum is in canola grown on pulse previous crop (114 ± 19.6 kg ha^{-1}). This yield penalty corresponds to 4.61% of the average adjusted predicted yield for previous crop pulse. This is reflected in the NR reduction which is largest for oilseed previous crop and smallest for pulse previous crop when nitrogen fertilizer use is reduced by 30% from the economic optimum.

Table 6-2 Yield and net revenue penalty estimates as a result of a reduction in N applied by 30% from the EONR which is based on annual average prices and variety index in 2019 (\$511 t^{-1} canola, \$1208 t^{-1} nitrogen, 103.9% of L252).

Economic OptN (kg/ha)	**Avg. Adj. Pred.Yield at Opt. N**[4]	**Reduction N (kg/ha)**	**App N (kg / ha)**	**Estimated Yield Penalty (kg/ha)**	**St. Errors**	**% Yield Penalty of Predicted Yield**	**NR Reduction ($/ha)**
			Oilseed Previous crop				
147	2504(251.3)	44.1	103	132	20.4	5.29	14.0
			Cereal Previous crop				
142	2491(251.4)	42.6	99.4	125	18.8	5.02	12.8
			Pulse Previous crop				
130	2461(252.5)	39.0	91.0	114	19.6	4.61	10.9

6.2.2 Economic Response to Reduced Nitrogen Fertilizer Application from the EONR

The economic response to reduced nitrogen application is shown in Figure 6-1. Figure 6-1 plots Table 6-1, where over the range of 0-60 kg ha^{-1} reduction in nitrogen applied in canola, the estimated reduction in producer net return increases exponentially from \$0-25.7 ha^{-1}. A

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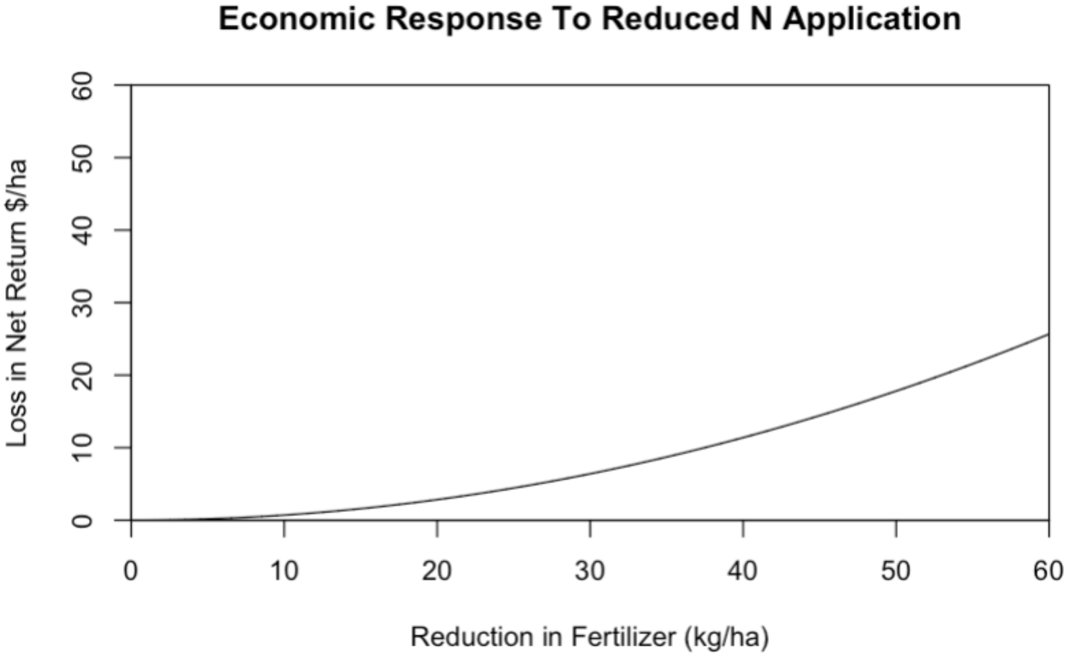
[4] Ibid.

reduction in nitrogen fertilizer by 20 kg ha^{-1} results in a modest loss of net return of \$2.85 ha^{-1}. Losses in net return increase as nitrogen fertilizer is reduced by greater quantities. A reduction in nitrogen fertilizer by 40 kg ha^{-1} results in a greater net return loses of \$11.4 ha^{-1}. At lower levels of reduction in fertilizer, there is a relatively low opportunity cost for GHG mitigation. This can be explained as marginal reductions in nitrogen fertilizer near the economic optimum result in lower costs, as marginal benefit diminishes towards the economic optimal rate of nitrogen. The loss in net returns is zero when nitrogen is at the economic optimum rate (Karatay & Meyer-Aurich, 2018) and increases quadratically as application rates move further away from the economic optimum. The modest losses of net return at even large deviations from the economic optimal N level supports previous findings of flat pay-off functions for crop production inputs at the field level (Pannell, 2006; Pannell, 2017). The wide profit plateau occurs due to the shape of the production function which is smooth with diminishing returns and therefore marginal profitability is close to zero in the region of the optimum (Pannell, 2006).

Figure 6-1 Economic response to reduced nitrogen fertilizer application for all previous crops (oilseed, cereal and pulse) from the EONR which is based on annual average prices and variety index in 2019 (\$511 t^{-1} canola, \$1208 t^{-1} nitrogen, 103.9% of L252).



6.2.3 Cost of GHG Mitigation from the EONR

Based on the direct emission factors associated with nitrogen application for a specific ecoregion, both the marginal and average cost of GHG mitigation associated with reduction in nitrogen fertilizer from the estimated economic optimal nitrogen rate can be plotted for both the brown and black soil zone as shown in Figure 6-2 and Figure 6-3. The larger the associated emissions from nitrogen application, the lower the GHG mitigation cost. This is shown in our results, as the estimated direct N_2O emissions from nitrogen application are lower for the brown soil zone relative to the black soil zone. Therefore, the GHG mitigation cost from reducing nitrogen fertilizer applied is the greatest for the brown soil zone. Conversely, the higher rates of emissions associated with nitrogen fertilizer application in the black soil zone results in a lower GHG mitigation cost from reducing nitrogen fertilizer application rates in this ecoregion.

Figure 6-2 shows the marginal GHG mitigation cost for both the black and brown soil zones. The marginal GHG mitigation cost is linear as a constant emissions factor is used, and the change in net return is a linear function derived from the quadratic canola profit function. The marginal GHG mitigation cost equals the 2022 social cost of carbon of \$50 t^{-1} CO_2eq when reducing nitrogen rates from the EONR by 6 kg ha^{-1} for the black soil zone and 3 kg ha^{-1} for the brown soil zone. The marginal GHG mitigation cost equals the 2030 scheduled social cost of carbon of \$170 t^{-1} CO_2eq when reducing nitrogen rates from the EONR by 19 kg ha^{-1} for the black soil zone and 9 kg ha^{-1} for the brown soil zone.

The GHG Mitigation Cost shown in Figure 6-3 is calculated using equation 3-15. Over the range of reducing nitrogen fertilizer application rates by 0 - 60 kg ha^{-1} from the economic optimum, the GHG mitigation cost ranges from \$0 – 762 t^{-1} CO_2eq for the brown soil zone. In the black soil zone, the GHG mitigation cost from a reduction of nitrogen fertilizer application rates by 0 - 60 kg ha^{-1} ranges from \$0 – 371 t^{-1} CO_2eq. At a 20 kg ha^{-1} reduction in nitrogen fertilizer from the economic optimum, the GHG mitigation cost is estimated to be \$190 t^{-1} CO_2eq for the brown soil zone and \$92.1 t^{-1} CO_2eq for the black soil zone. The higher GHG mitigation cost for the brown soil zone is due to the relatively modest nitrous oxide emissions associated with nitrogen application in the brown soil zone, relative to those of the black soil zone. At a 40 kg ha^{-1} reduction in nitrogen fertilizer from the economic optimum, the GHG mitigation cost is estimated to be \$381 t^{-1} CO_2eq for the brown soil zone and \$185 t^{-1} CO_2eq for the black soil zone.

Figure 6-2 Marginal costs of greenhouse gas mitigation from N fertilizer reduction for all previous crops (oilseed, cereal, and pulse) for the brown soil zone (EF = 0.0016) and the black soil zone (EF = 0.0033).

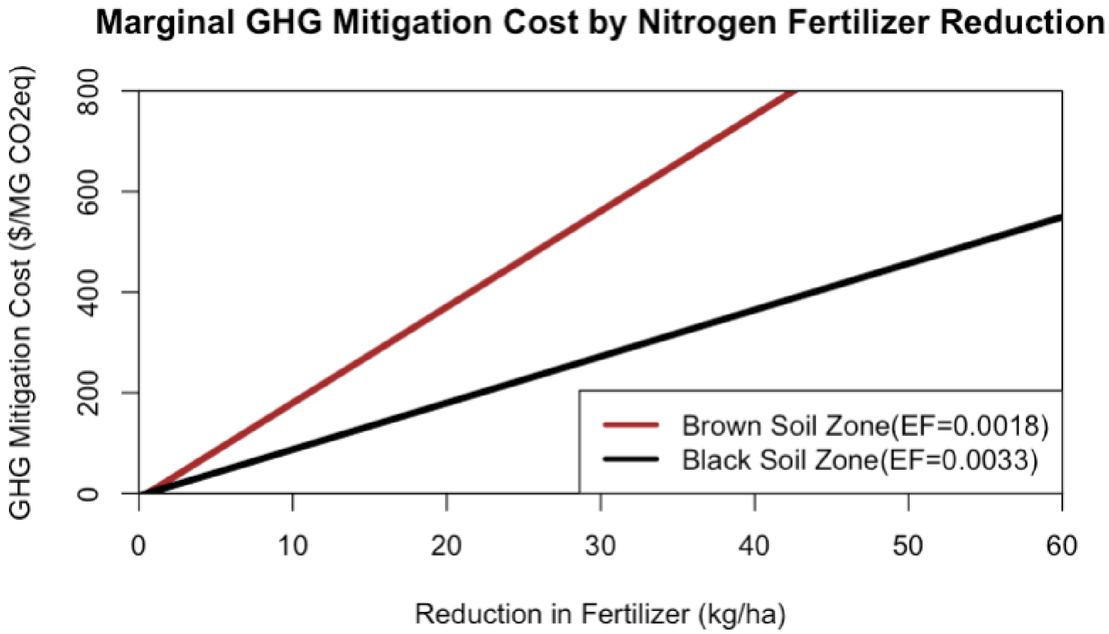
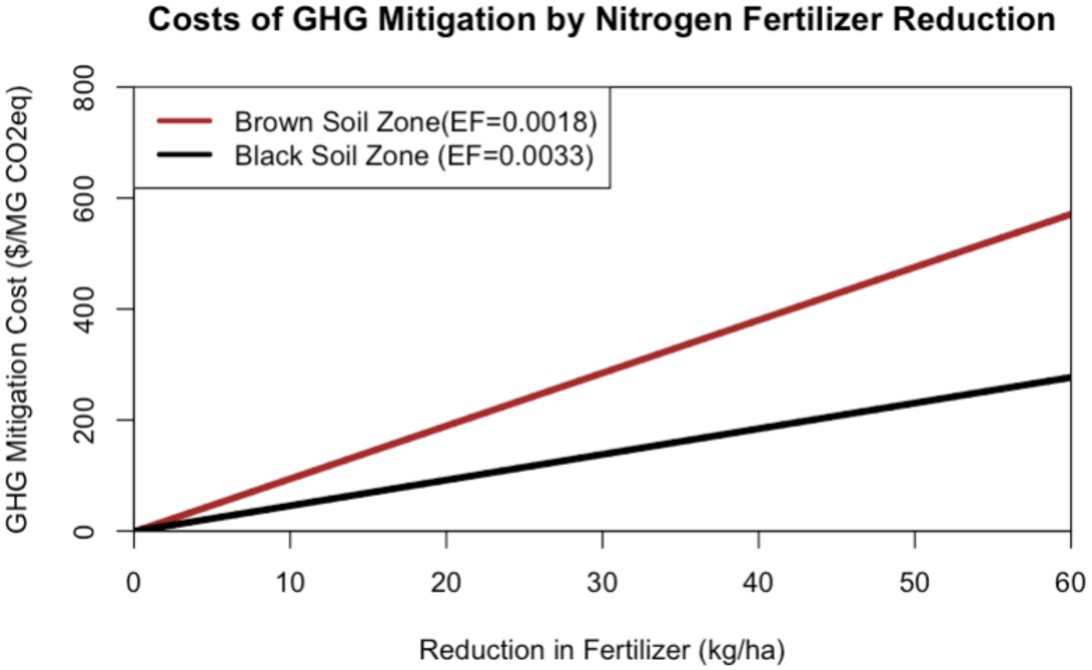


Figure 6-3 Costs of greenhouse gas mitigation from N fertilizer reduction for all previous crops (oilseed, cereal, and pulse) for the brown soil zone (EF = 0.0016) and the black soil zone (EF = 0.0033).



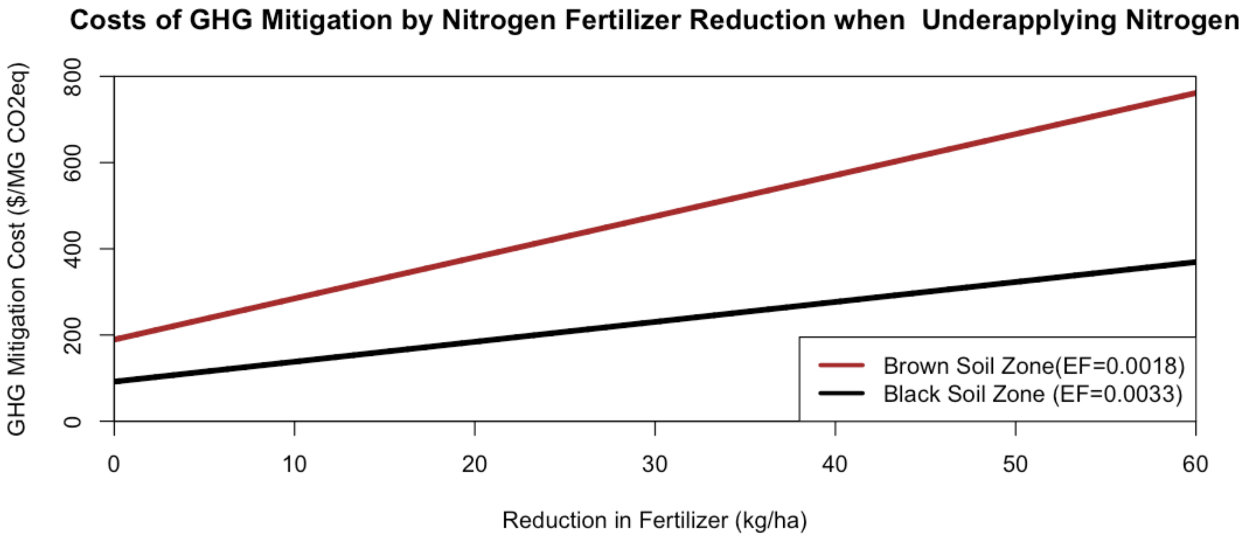
6.2.4 GHG Mitigation Cost from Suboptimal Rates

In the above sections 6.2.2 and 6.2.3, the GHG mitigation cost estimates as a result of reduced nitrogen application rates are relative to the estimated economic optimal rate. However, actual producer application rates may vary widely and are not necessarily at the EONR due to imperfect information, equipment constraints, and/or credit constraints, etc. To demonstrate the potential effects of producers applying nitrogen at suboptimal rates on the GHG mitigation cost, the case of producers underapplying and overapplying nitrogen by 10 kg ha^{-1} relative to the estimated economically optimal nitrogen rate is explored. The GHG mitigation cost of nitrogen fertilizer reduction from the estimated economic optimal rate for all previous crops was shown in Figure 6-3 and can be compared to Figure 6-4 where the GHG mitigation cost is shown in the case of both under and over applying nitrogen. Panel A of Figure 6-4 shows the GHG mitigation cost from fertilizer reduction in the case of underapplying nitrogen by 10 kg ha^{-1} relative to the estimated optimal nitrogen rate. Over the range of reducing nitrogen fertilizer application rates by 0 - 60 kg ha^{-1} from the suboptimal nitrogen rate, the GHG mitigation cost ranges from \$0 – 759 t^{-1} CO_2eq for the brown soil zone. In the black soil zone, the GHG mitigation cost from a reduction of nitrogen fertilizer application rates by 0 - 60 kg ha^{-1} from the suboptimal rate ranges from \$0 – 368 t^{-1} CO_2eq. At a 20 kg ha^{-1} reduction in nitrogen fertilizer from the suboptimal rate, the GHG mitigation cost is estimated to be \$378 t^{-1} CO_2eq for the brown soil zone and \$183 t^{-1} CO_2eq for the black soil zone. At a 40 kg ha^{-1} reduction in nitrogen fertilizer from the suboptimal rate, the GHG mitigation cost is estimated to be \$569 t^{-1} CO_2eq for the brown soil zone and \$276 t^{-1} CO_2eq for the black soil zone. These results indicate that the GHG mitigation cost from nitrogen fertilizer reduction is greater in the case of producers who are underapplying nitrogen relative to producers who are applying nitrogen at the economic optimal rate.

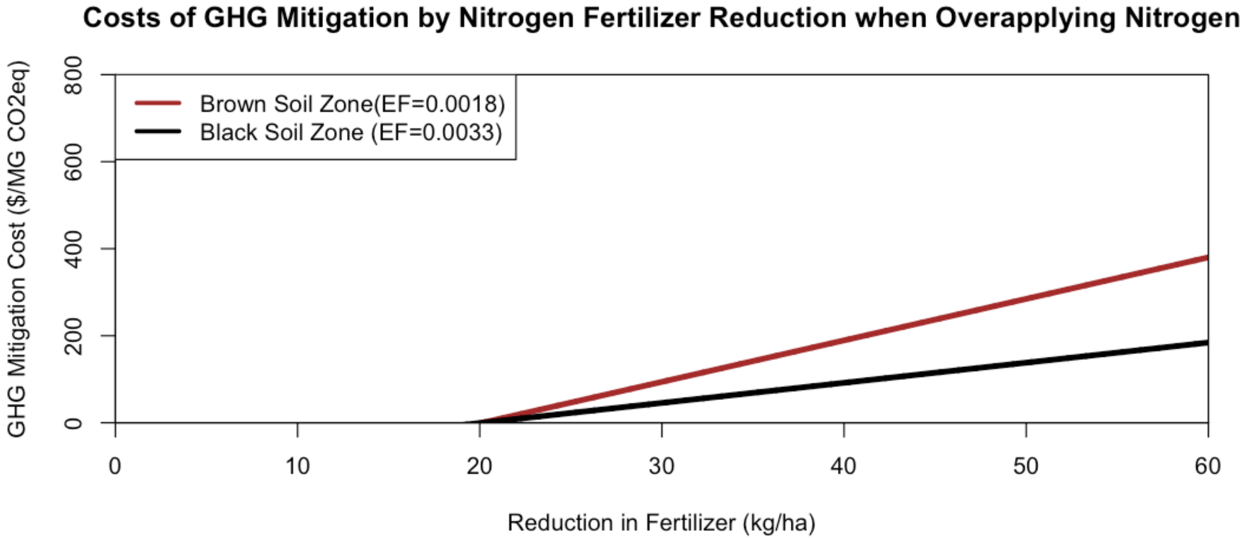
Panel B of Figure 6-4 shows the GHG mitigation cost from fertilizer reduction in the case of overapplying nitrogen by 10 kg ha^{-1} relative to the estimated optimal nitrogen rate. Over the range of reducing nitrogen fertilizer application rates by 0 - 60 kg ha^{-1} from an overapplication of nitrogen by 10 kg ha^{-1} from the EONR, the GHG mitigation cost ranges from \$0 – 387 t^{-1} CO_2eq for the brown soil zone. In the black soil zone, the GHG mitigation cost from a reduction of nitrogen fertilizer application rates by 0 – 60 kg ha^{-1} ranges from \$0 – 183 t^{-1} CO_2eq. At a 40 kg ha^{-1} reduction in nitrogen fertilizer, the GHG mitigation cost is estimated to be \$187 t^{-1} CO_2eq for the brown soil zone and \$91 t^{-1} CO_2eq for the black soil zone. These results indicate that in the case of producers overapplying nitrogen relative to the EONR, the GHG mitigation cost from reducing nitrogen fertilizer is smaller relative to producers that are applying nitrogen at the economic optimal rate.

Figure 6-4 Under conditions of underapplying (Panel A) and overapplying (Panel B) nitrogen by 10 kg ha^{-1} from the EONR the costs of greenhouse gas mitigation from N fertilizer reduction for all previous crops (oilseed, cereal and pulse) for the brown soil zone (EF = 0.0016) and the black soil zone (EF = 0.0033).

Panel A



Panel B



This section demonstrates the potential effects of reducing nitrogen fertilizer applied in the circumstances where producers are applying nitrogen at suboptimal rates relative to the economic optimum. Based on the annual cost ratios and crop insurance data used in this thesis, it appears that on average producers are mainly near or slightly below the estimated economic optimal nitrogen rate. The estimated optimal nitrogen application rate by annual average cost ratios compared to the annual observed average nitrogen rate in the data sample are shown in Table 5-9. The annual data appears to show producers on average closing in on the estimated optimal nitrogen rate across all previous crop types. In 2019, across all previous crop types, producers on average were applying within the estimated optimal rate standard errors. However, individual producers' input and output cost ratio are unknown, and the rate of nitrogen applied varies among producers. Therefore, it is important to consider the potential effects of producers over-applying or under-applying nitrogen on the GHG mitigation cost. In the case of producers already under-applying nitrogen relative to the economic optimal rate, a policy that reduces nitrogen application will result in larger GHG mitigation costs relative to the case where producers are applying at the EONR. Conversely, if producers are over-applying nitrogen relative to the economic optimal rate, this would result in lower GHG mitigation costs relative to the case where producers are applying at the EONR.

6.3 Tax on Nitrous Oxide Emissions Policy Scenario

This section focuses on a scenario where a tax is applied on direct nitrous oxide emissions from nitrogen fertilizer application in Saskatchewan using the Government of Canada's social cost of carbon. The results of the impact of a nitrous oxide tax on the estimated economic optimal nitrogen application rate, yield, net return and GHG emissions are provided in this section.

6.3.1 Economic Optimum, Yield Penalty, Net Return and GHG Emissions Post Tax

The estimated change in economic optimal nitrogen application from a tax on nitrous oxide emissions are reported in Table 6-3 by previous crop. The results include the estimated yield penalty, change in net return and reduction in GHG emissions as a result of a nitrous oxide tax. Under a tax on N_2O emissions from nitrogen application based on the Government of Canada's own current social cost of carbon (\$50 t^{-1} CO_2eq), the range of reduction in nitrogen application from the estimated optimal rate varies across previous crop type and is estimated to be 2.04-

2.31% for the brown soil zone and 3.40– 4.62% for the black soil zone. When applying a tax on N_2O emissions using the Government of Canada's future scheduled cost of carbon for 2030 (\$170 t^{-1} CO_2eq), the range of reduction in nitrogen application from the estimated optimal rate is estimated to be 6.12 – 6.92% for the brown soil zone and 12.3 – 14.6% for the black soil zone.

At the current social cost of carbon (\$50 t^{-1} CO_2eq) for the brown soil zone which has the lowest emissions factor considered (EF=0.0016), the added tax of \$37.46 t^{-1} of nitrogen resulted in a relatively small reduction in the optimal nitrogen rate, moving from 142 ± 15.5 kg N ha^{-1} for canola grown on cereal previous crop. This is estimated to result in a yield penalty of 6.64 ± 1.32 kg ha^{-1} with a total loss of net return of \$5.26 ha^{-1} and a reduction in GHG emissions by 2.07 kg CO_2eq ha^{-1}. For reference, a reduction in yield by 6.64 kg ha^{-1} corresponds to a 0.27% yield penalty of the average adjusted predicted yield.

At the future social cost of carbon (\$170 t^{-1} CO_2eq) for the black soil zone which has the highest emissions factor considered (EF= 0.033), the added tax of \$262.71 t^{-1} of nitrogen resulted in a relatively large reduction in the optimal nitrogen rate, moving from 142 ± 15.5 kg N ha^{-1} to 123 ± 15.8 kg N ha^{-1} for canola grown on cereal previous crop. This is estimated to result in a yield penalty of 49.2 ± 8.49 kg ha^{-1} with a total loss of net return of \$34.9 ha^{-1} and a reduction in GHG emissions by 29.0 kg CO_2eq ha^{-1}. For reference, a reduction in yield by 49.2 kg ha^{-1} corresponds to a 1.98% yield penalty of the average adjusted predicted yield.

Table 6-3 Estimated optimal nitrogen rate by previous crop under a nitrous oxide tax for the black and brown soil zone and at two carbon prices ($50 and 170 CO_2 eq t^{-1}).

Soil Zone, EF	**CO_2 Price ($ CO_2 eq t^{-1})**	**Tax_N ($ t^{-1})**	**W_N + Tax_N ($ t^{-1})**	**Post Tax CR**	**Prev. crop**	**Opt. N Rate (kg ha^{-1})[5]**	**SE**	**Post Tax Opt. N Rate (kg ha^{-1})**	**SE**	**Yield Penalty (kg ha-^{1})**	**SE**	**% Yield Penalty of Predicted Yield [6]**	**P_C*Yield Penalty – W_N*Δ in N Rate ($/ha)**	**Tax_N * Post Tax N Rate ($/ha)**	**Loss of Net Return ($/ha)**	**Reduction in GHG (kg CO2eq ha^{-1})**
Brown 0.0016	50	37.46	1245	2.44	Cereal	142	17.5	139	17.0	6.64	1.32	0.27	0.05	5.20	5.26	2.07
					Oilseed	147	19.1	144	18.5	7.96	1.72	0.32	0.07	5.41	5.49	2.48
					Pulse	130	17.5	127	17.4	7.36	1.49	0.30	0.06	4.76	4.83	2.29
Brown 0.0016	170	127.37	1335	2.61	Cereal	142	17.5	133	16.3	21.8	4.09	0.87	0.54	16.9	17.5	6.57
					Oilseed	147	19.1	138	17.6	23.2	4.70	0.93	0.61	17.6	18.2	6.97
					Pulse	130	17.5	121	17.3	22.5	4.39	0.92	0.58	15.4	16.0	6.79
Black 0.0033	50	77.27	1285	2.52	Cereal	142	17.5	136	16.6	14.1	2.72	0.57	0.23	10.5	10.7	8.91
					Oilseed	147	19.1	142	18.1	12.9	2.73	0.52	0.20	10.9	11.1	8.20
					Pulse	130	17.5	124	17.3	14.8	2.94	0.60	0.26	9.61	9.86	9.37
Black 0.0033	170	262.71	1471	2.88	Cereal	142	17.5	123	15.8	49.2	8.49	1.98	2.50	32.4	34.9	29.0
					Oilseed	147	19.1	129	16.6	47.9	8.92	1.91	2.40	33.8	36.2	28.3
					Pulse	130	17.5	111	17.9	50.1	9.25	2.03	2.58	29.3	31.9	29.5

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[5] In this policy scenario, the EONR is based on 2019 average variety index (103.9%) and annual prices where the price of nitrogen (W_N) is $1208 $t^{-1,}$ the expected price of canola (P_C) is $511 t^{-1} which equates to a cost ratio (CR) of 2.36 before a tax on nitrous oxide emissions (Tax_N) is applied to nitrogen fertilizer.[6] The predicted yields were derived using the 'predictions' function in the *MarginalEffects* package. The average adjusted predictions are reported based on the specified nitrogen rate and previous crop type and the mean(or mode) for all other categories The mean/mode for the reference categories used in making this predicted yield include: using an average canola yielding customer, risk zone 17, soil class G, year 2015, 32 phosphorous, 4 potassium, 22.8 sulphur, variety index 93%. Average predicted yield at optimal nitrogen for cereal, oilseed and pulse was 2409 (252.2), 2397 (251.9) and 2374 (251.6) kg ha^{-1} respectively.

6.4 Comparison of 1) Private Optimum, 2) Social Optimum and 3) 30% Nitrogen Rate Reduction

6.4.1 Graphical Representation

The economic optimum for nitrogen fertilizer application for canola grown following a pulse crop can be depicted in graphical form, as shown in Figure 6-5 and Figure 6-6. The N_2O tax in Figure 6-5 was calculated using the current social cost of carbon for 2022 (\$50 CO_2eq t^{-1}) while the N_2O tax in Figure 6-6 was calculated using the future scheduled social cost of carbon for 2030 (\$170 CO_2eq t^{-1}). In this graphical representation, the scenario considered is that of canola seeded on a field previously cropped to a pulse in the black soil zone. Therefore, the black soil ecoregion emissions factor was used, which is the highest emissions factor of the two ecoregions. The calculation of VMP_N as shown in equation 6-1 utilizes the coefficients from the estimated canola production function. In this scenario, the annual average 2019 prices for canola and nitrogen were used (\$0.511 and \$1.210 kg^{-1}) as well as the 2019 average variety index (103.9% of L252). To visualize the different effects of environmental policies Figure 6-5 and Figure 6-6 graphs the private optimum, social optimum (referring to the N_2O tax) and 30% reduction in N rate using the current and future Canadian social costs of carbon. This is followed by a description of each scenario and the associated welfare effects.

6-1

$$W_N = VMP_N$$

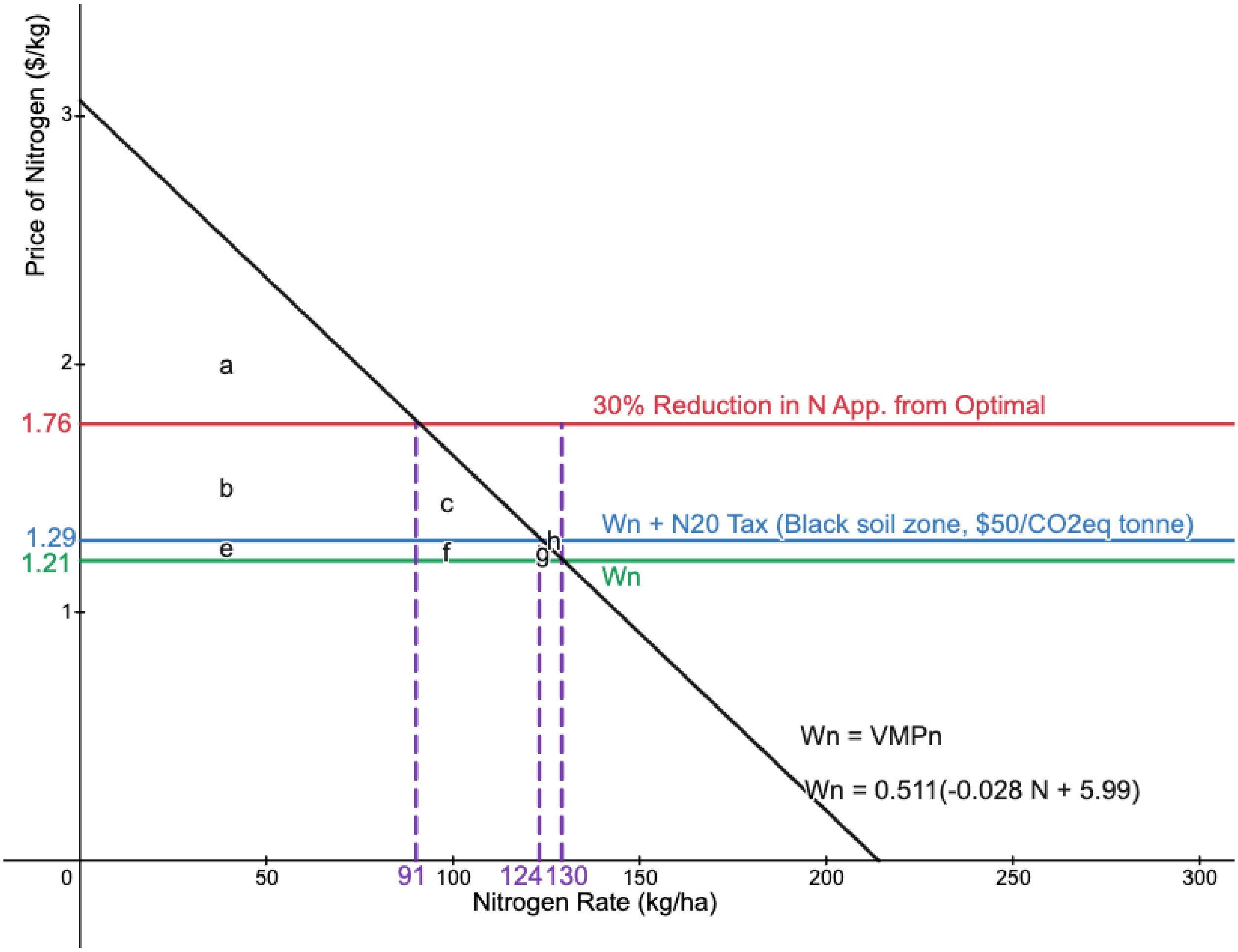
$$W_N = P_c * MP_N$$

$$W_N = P_C * (b18 + 2 * N * b19 + b21 + b22 * Variety\ Index)$$

$$W_N = 0.511 * (b18 + 2 * N * b19 + b21 + b22 * 103.9)$$

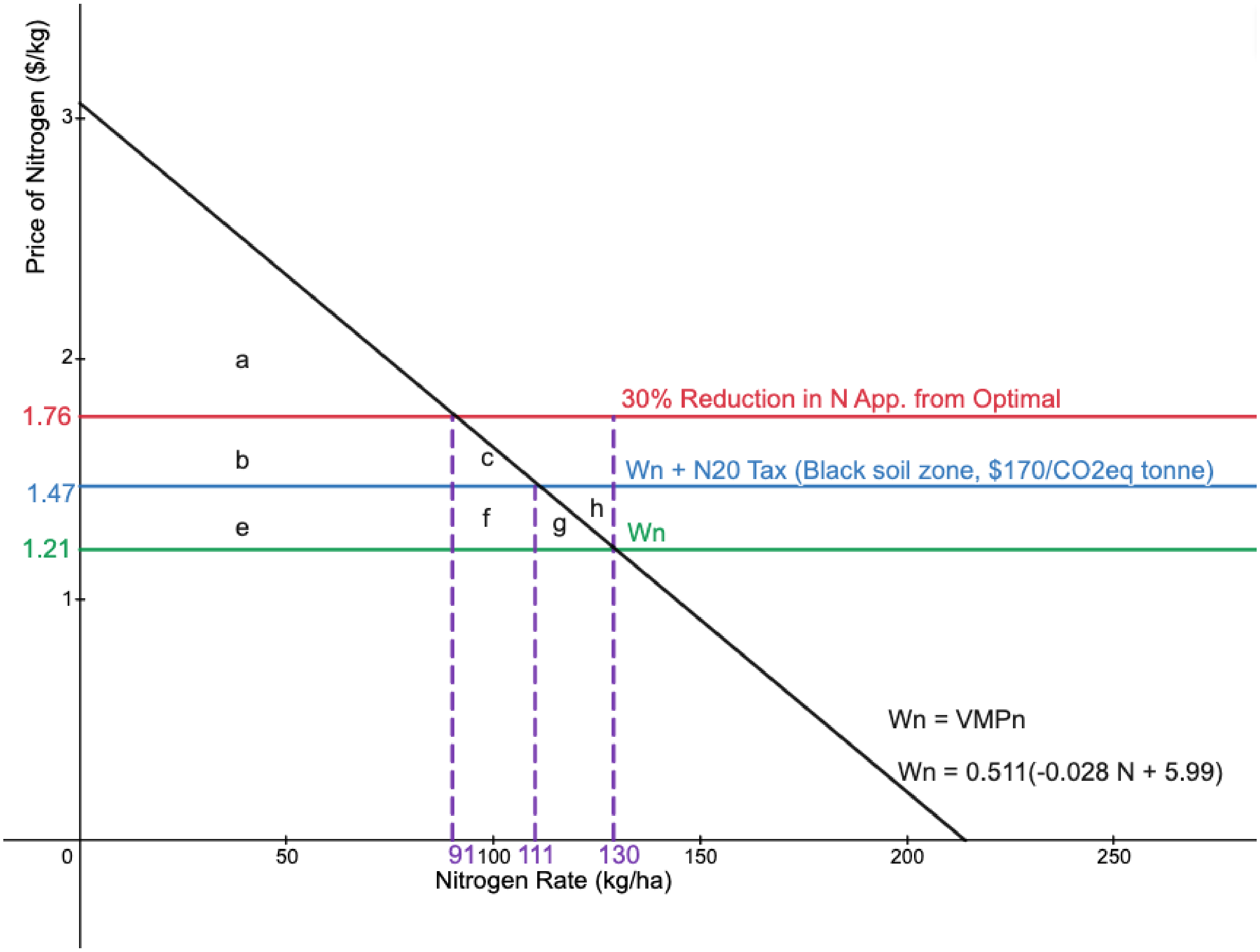
$$W_N = 0.511 * (-0.0280 * N + 5.99)$$

Figure 6-5 Comparison of three scenarios: privately optimal, socially optimal (N_2O tax), and a 30% reduction in N application using the carbon price of **\$50/ CO_2eq tonne.**



Note: This graphical representation is for the previous crop pulse and the black soil zone.
Graph tool: (Desmos, 2022)

Figure 6-6 Comparison of three scenarios: privately optimal, socially optimal (N_2O tax), and a 30% reduction in N application using the carbon price of **\$170/ CO_2eq tonne**.



Note: This graphical representation is for the previous crop pulse and the black soil zone.
Graph tool: (Desmos, 2022)

6.4.2 *Privately Optimal*

The average annual price of nitrogen was \$1.21 kg^{-1} was used as the value for w_N in this graphical representation scenario. In the privately optimal case, the optimal applied rate of nitrogen is where VMP_N intersects with w_N which occurs at the nitrogen rate of 130 kg ha^{-1} in the case of fields previously cropped to a pulse. The maximum canola yield occurs at 214 kg ha^{-1}. The privately optimal case results in the maximum producer surplus equal to the area $a + b + c + e + f + g$. The social cost of carbon at a nitrogen rate of 130 kg ha^{-1} is equal to the area e + f + g + h. The overall welfare is equal to areas *a* + *b* + *c* – *h*, as area *h* is the negative externality of pollution from nitrogen fertilizer application.

6.4.3 Socially Optimal Rates

The socially optimal rate of nitrogen applied occurs where VMP_N intersects with $w_N + N_2O\ tax$ which occurs at 124 kg ha^{-1} at the current social cost of carbon (Figure 6-5) and at 111 kg ha^{-1} at the future social cost of carbon (Figure 6-6). The N_2O tax was calculated using both the current and future national carbon price and the emissions factor for the black soil zone. Under the current social cost of carbon of \$50 CO_2eq t^{-1} this is equivalent to a N_2O tax of \$0.08 kg^{-1} N. The N_2O tax using the future scheduled national carbon price for 2030 (\$170 CO_2eq t^{-1}) which is equivalent to a tax of \$0.26 kg^{-1} N. In the socially optimal case, the producer surplus is equal to the area *a* + *b* + *c* while the social cost of carbon is equal to area *e* + *f*.

6.4.4 30% Reduction in N App from Optimum

After a 30% reduction in nitrogen application from the optimal the application rate of nitrogen is reduced to 91 kg N ha^{-1}. Producers reduce nitrogen application by 30% when w_N is equal to \$1.76 kg^{-1} N. Therefore, the tax on nitrogen required to reduce nitrogen application by 30% is \$0.55 kg^{-1} N when using the average annual price of urea for 2019. In the case of a 30% reduction in nitrogen application, the producer surplus is equal to the area *a*. The government revenue generated from a \$0.55 kg^{-1} N tax on nitrogen is equal to area *b*. The dead weight loss from under application of nitrogen fertilizer is equal to the area *c*.

6.4.5 Welfare Effects

The graphical comparison of the private optimum, a 30% nitrogen fertilizer reduction and a tax on N_2O emissions allows for the comparison of the welfare effects of these three scenarios. The area values for Figure 6-5 and Figure 6-6 are shown in Table 6-4. These values are the basis of the welfare effects or the comparison of three scenarios: privately optimal, socially optimal (N_2O tax), and the a 30% reduction in N application using \$50 CO_2eq t^{-1} (Figure 6-5) and \$170 CO_2eq t^{-1} (Figure 6-6) shown in Table 6-5.

Table 6-4 Graph area values for Figure 6-5 and Figure 6-6.

Graph area	\$50 CO_2eq t^{-1} Figure 6-5 **(\$ ha^{-1})**	\$170 CO_2eq t^{-1} Figure 6-6 **(\$ ha^{-1})**
a	59.19	59.19
b	42.77	26.39
c	7.76	2.90
e	7.28	23.66
f	2.64	5.20
g	0.24	2.47
h	0.24	2.47

Table 6-5 Welfare effects for three scenarios: privately optimal, socially optimal (N_2O tax), and the a 30% reduction in N application using \$50 CO_2eq t^{-1} (Figure 6-5) and \$170 CO_2eq t^{-1} (Figure 6-6).

Social Cost of Carbon	**Scenario**	**N Price** kgha^{-1}	**N Rate** kgha^{-1}	**Producer Surplus**	**Social Cost of Carbon**	**Pigouvian Tax Revenue**	**DWL**	**Total Welfare**
\$50	Privately Optimal	130	1.21	*abcefg* \$120.0 ha^{-1}	*efgh*. \$10.40 ha^{-1}			*abc-h* \$109.5 ha^{-1}
	Socially Optimal	124	1.29	*abc* \$109.7 ha^{-1}	*ef* \$9.92 ha^{-1}	*ef* \$9.92ha^{-1}		*abc* \$109.7 ha^{-1}
	30% Reduction in Fert App	91	1.76	*a* \$59.2 ha^{-1}	*e* \$7.28 ha^{-1}	*be* \$50.05 ha^{-1}	*c* \$7.76 ha^{-1}	*ab* \$102.0 ha^{-1}
\$170	Privately Optimal	130	1.21	*abcefg* \$ 120.0 ha^{-1}	*efgh*. \$33.8 ha^{-1}			*abc-h* \$86.01 ha^{-1}
	Socially Optimal	111	1.47	*abc* \$88.48 ha^{-1}	*ef* \$28.86 ha^{-1}	*ef* \$28.86 ha^{-1}		*abc* \$88.48 ha^{-1}
	30% Reduction in Fert App	91	1.76	*a* \$59.19 ha^{-1}	*e* \$23.66 ha^{-1}	*be* \$50.05 ha^{-1}	*c* \$2.91 ha^{-1}	*ab* \$85.58 ha^{-1}

At the current social cost of carbon (\$50 CO_2eq t^{-1}), in the privately optimal scenario, producer surplus is the greatest at \$120.0 ha^{-1}. However, the negative externality of pollution from nitrogen fertilizer application reduces the total welfare to \$109.5 ha^{-1}. The overall welfare is greatest in the N_2O tax (social optimum) scenario at \$109.7 ha^{-1} which is also equal to the producer surplus. The overall welfare is the lowest in the scenario where fertilizer application is reduced 30%, with overall welfare estimated to be \$102.0 ha^{-1} Fertilizer application reduced by 30% is estimated to greatly reduce producer welfare to \$59.2 ha^{-1}.

At the future social cost of carbon (\$170 CO_2eq t^{-1}), the privately optimal scenario again results in the greatest producer surplus is the greatest at \$120.0 ha^{-1}. However, the negative externality of pollution from nitrogen fertilizer application greatly reduces the overall welfare to \$86.01. The overall welfare is greatest in the N_2O tax (social optimum) scenario at \$88.48 ha^{-1} which is also equal to the producer surplus. In the scenario where fertilizer application is reduced 30%, the overall welfare is estimated to be \$85.58 ha^{-1} while producer welfare is reduced to \$59.19 ha^{-1}. At the future cost of social carbon, this scenario again results in the lowest overall welfare relative to the social optimum and the privately optimal scenarios.

6.4.6 Summary

The estimated welfare effects indicate that for both the current (\$50 CO_2eq t^{-1}) and future social cost of carbon (\$170 CO_2eq t^{-1}) the policy scenario that results in the greatest overall welfare is the N_2O tax (social optimum). In the privately optimal scenario, the negative externality of pollution from nitrogen fertilizer application reduces overall welfare relative to the social optimum. However, when a policy is imposed to reduce nitrogen fertilizer application rates by 30%, our estimates suggest this is an overly restrictive policy even when using the federal government's highest scheduled carbon price for 2030 of \$170 CO_2eq t^{-1}. This policy would greatly reduce canola producers' welfare as well as create a dead weight loss to society.

6.5 Discussion of Nitrogen Fertilizer Application Reduction Scenario Results

A reduction in nitrogen fertilizer applied from the estimated economic optimum resulted in a loss in canola grower's net return. This is due to the yield penalties outweighing the savings in fertilizer costs (Karatay & Meyer-Aurich, 2018). At lower levels of reduction in fertilizer, there is a relatively low opportunity cost for GHG mitigation. A reduction in nitrogen fertilizer by 20 kg ha^{-1} results in a modest loss of net return of \$2.77-2.90 ha^{-1} while a reduction in nitrogen fertilizer by 40 kg ha^{-1} results in a greater net return loss of \$11.30-11.60 ha^{-1}. The loss in net returns are relatively small when nitrogen is applied near the economic optimum rate (Karatay & Meyer-Aurich, 2018). Policies that reduce nitrogen use at levels near the optimal rate are estimated to be quite modest, however larger reductions in nitrogen applied from the economic optimum will more negatively impact canola producers' net return. The modest losses of net return at even large deviations from the economic optimal level of N supports previous findings of flat pay-off functions for nitrogen in crop production (Pannell, 2006; Pannell, 2017). Previous estimates of the economic response to reduced nitrogen fertilizer on producer net return have been conducted in Germany based on long-term experiments for wheat and rye. Karatay & Meyer found that a reduction in 20 kg ha^{-1} of nitrogen from the optimum resulted in net return losses ranging from £6 – 18 ha $^{-1}$ for wheat and £8 – 23 /ha for rye (Karatay & Meyer-Aurich, 2018).

The cost of GHG mitigation for nitrous oxide emissions from nitrogen application in Canola in the black and brown soil zone was estimated. At a 20 kg ha^{-1} reduction in nitrogen fertilizer from the economic optimum, the GHG mitigation cost is estimated to be \$190 CO_2eq t^{-1} for the brown soil zone and \$92.1 CO_2eq t^{-1}for the black soil zone. At a 40 kg ha^{-1} reduction in nitrogen fertilizer from the economic optimum, the GHG mitigation cost is estimated to be \$381 CO_2eq t^{-1} for the brown soil zone and \$185 CO_2eq t^{-1} for the black soil zone. The higher GHG mitigation cost for the brown soil zone is due to the relatively modest nitrous oxide emissions associated with nitrogen application in the brown soil zone, relative to those of the black soil zone. While to the author's knowledge, there have been no studies looking at the marginal abatement cost of nitrous oxide emissions from nitrogen application in Canola on the Canadian prairies a previous study by Karatay & Meyer (2018) can be examined for reference. This study included both indirect and direct nitrous oxide emissions from nitrogen application (Karatay & Meyer-Aurich, 2018). This study found that the costs of GHG mitigation at a reduced nitrogen rate of 20 kg ha^{-1} from the economic optimum over five yield zones ranged from £ 28-93 ha^{-1} for wheat and 39-115 ha^{-1} for rye.

The results of this section have important implications for policy makers as the Government of Canadian government has set targets to reduce GHG emissions from nitrogen fertilizer by 30% by the year 2030 from 2022 levels. One approach to reducing nitrogen fertilizer emissions may be through reduced nitrogen rates. The estimated reductions in net return and GHG mitigation cost provided in this section are a starting point to understanding the potential effects of such a strategy.

6.6 Discussion of Tax on Nitrous Oxide Emission Results

This study assessed the potential effects of a tax on direct nitrous oxide emissions from nitrogen fertilizer application. The changes in optimal nitrogen application rates, yield penalties and change in net return were estimated. These results indicate that this policy could have potential impacts on nitrogen fertilizer use and subsequent net return for Saskatchewan canola producers. When applying the 2030 social cost of carbon (\$170 CO_2eq t^{-1}), the added tax to nitrogen is \$262.71 t^{-1} of nitrogen based on the black soil zone EF and 127.37 t^{-1} based on the brown soil zone EF. For reference, the average price of nitrogen in 2019 was \$1208. A tax using the black soil zone EF and future carbon price would amount to over 20% of the average nitrogen price in 2019 which is estimated to reduce nitrogen from the EONR by 12.3 – 14.6% in the black soil. At the future social cost of carbon, producers are estimated to experience reduced net return with loses of \$13.98 - 16.12 ha^{-1} estimated for the brown soil zone and \$27.78 - 28.46 ha^{-1} estimated for the black soil zone. Under a nitrous oxide tax based on the scheduled 2030 price of carbon, the reduction in GHG emissions is estimated as 6.57 – 6.79 kg CO_2 eq ha^{-1} for the brown soil zone and 28.3 – 29.5 kg CO_2 eq ha^{-1}. The benefits of reduced emissions relative to the penalties for yield and net return must be deliberated by policy makers. These results aim to provide insight on the potential impacts of a N_2O tax on application rates, yield penalties, net return, and GHG emissions in the case of Saskatchewan canola.

6.7 Discussion of Comparison of 1) Private Optimum, 2) Social Optimum and 3) 30% Nitrogen Rate Reduction

The estimated welfare effects indicate that for both the current (\$50 CO_2eq t^{-1}) and future social cost of carbon (\$170 CO_2eq t^{-1}) the policy scenario that results in the greatest overall welfare is the N_2O tax (social optimum). In the privately optimal scenario, the negative externality of pollution from nitrogen fertilizer application reduces overall welfare relative to the social optimum. However, when a policy is imposed to reduce nitrogen fertilizer application rates by 30%, our estimates suggest this is an overly restrictive policy even when using the federal government's highest scheduled carbon price for 2030 of \$170 CO_2eq t^{-1}. This policy would greatly reduce canola producers' welfare as well as create a dead weight loss to society. Applying a tax on nitrous oxide emissions using the governments' own social cost of carbon schedule is estimated to reduce fertilizer use by a rate less than 30% when only accounting for direct emissions. From a socially optimal nitrous oxide tax, fertilization rates are estimated to be reduced by 12.3 – 14.6% in the black soil zone and 6.12 – 6.92% in the brown soil zone from the economic optimum at the 2030 social cost of carbon of \$170t^{-1}. The socially optimal reduction in fertilization rates is estimated to be 3.40 – 4.62% in the black soil zone and 2.04 - 2.31% in the brown soil zone from the economic optimum at the current social cost of carbon of \$50 t^{-1}. The 4R's of Nutrient Stewardship are the right source at the right rate, right time, and right place. It is important to note that according to the estimates of the economic optimal nitrogen applied rate in this thesis, producers appear to currently on average by applying nitrogen near or slightly below the economic optimal nitrogen rate. Therefore, policies aimed at the other 4R's of Nutrient Stewardship may be more favourable to reduce emissions from nitrogen fertilizer. Focus on agronomic research, extension, and policy to improve nitrogen management and optimize fertilizer use are other opportunities to reduce emissions (Government of Canada, 2022).

This section compared the private optimum, a scenario with a tax on N_2O emissions at the Government of Canada's social cost of carbon, and a scenario 30% nitrogen fertilizer reduction with. This included assessment of the welfare effects including producer surplus, social cost of carbon, tax revenue and dead weight loss. However, more analysis on policy scenarios such as these is required for a more complete understanding of the potential effects. The far-reaching impacts of policy may be numerous but were beyond the scope of this study. For example, in the case of a policy that reduces nitrogen fertilizer use in Saskatchewan to the extent that yields are significant diminished, one potential outcome may be a shift in production to other areas of the world to meet global demand. The environmental impacts of such a potential shift must also be considered when assessing the effectiveness of a policy. As shifting canola production to areas of the world with less environmentally stringent policies may conceivably increase overall global emissions, these are important potential impacts of policy that must be considered by policy makers and are areas for future research.

6.8 Chapter Summary

This chapter compared the scenarios of the privately optimal, socially optimal (a tax on N_2O emissions using the Government of Canada's social cost of carbon) and a 30% nitrogen fertilizer reduction. This comparison included estimated welfare effects to aid policy makers as the Government of Canada has set targets for reduced GHG emission from nitrogen fertilizer of 30% by the year 2030 from 2020 levels. A tax on N_2O emissions using the Government of Canada's social cost of carbon was assessed including estimating the post-tax economic optimal rate and the resulting yield and net return penalties as well as GHG reduction. Under a scenario of reduced nitrogen fertilizer application, yield and net return penalties, economic response, and marginal costs of GHG mitigation were estimated. The potential effects of nitrogen rates that are above or below the EONR on the marginal costs of GHG mitigation were also explored. These results were provided in the hopes that they provide insight for policy makers and future researchers as Canada aims to meet the ambitious climate targets set for reduced emissions from nitrogen fertilizer application.

CHAPTER 7 CONCLUSIONS

7.1 Summary of Results and Main Implications

7.1.1 Canola Production Function

This thesis estimates the Saskatchewan canola yield response using a quadratic production function with fixed effects. The estimated results are reported with the important limitation that the use of fixed effects does not fully address the case of correlation between input levels and unobserved time-varying producer-specific shocks, in which case the estimates of this production function will be biased (Levinsohn & Petrin, 2003). The canola production function provides insight on a variety of factors that determine yield including nutrient application, herbicide system of variety, historical average rainfall, seeding date, previous crop, and fungicide application. The regression estimates from this model are used to calculate the marginal product of nitrogen application by previous crop and variety index.

7.1.2 Economic Optimal Nitrogen Applied Rates

The economic optimal nitrogen applied is estimated using the marginal production of nitrogen and is conditioned on the previous crop and variety index. The results estimated suggest that the optimal nitrogen application rates are greatest for oilseed previous crop and lowest for pulse previous crop. The results also indicate that as producers use higher yielding varieties, the optimal nitrogen application rate increases. This thesis estimates a range of optimal nitrogen application rates based on different cost ratios. This analysis included a range of canola prices of \$400 – 700/tonne and a range of nitrogen fertilizer costs from \$1000 – 1700/tonne in the economic analysis. A range of variety index values of 83.5-110% was used as well as previous crops of pulse, oilseed and cereal since the production function model is conditioned on previous crop and variety index. The estimated optimal nitrogen application rate ranges from 62.5 - 181 kg ha^{-1}. Using 2019 annual average prices for canola and nitrogen and the 2011-2019 mean variety index of 93%, the estimated economic optimum rate of nitrogen was 131, 125 and 114 kg N ha^{-1} for oilseed, cereal, and pulse previous crop. When using a higher variety index, such as the average in the dataset in 2019 of 103.9%, the estimated economic optimum rate of nitrogen was

147, 141 and 130 kg N ha^{-1} for oilseed, cereal, and pulse previous crop. From the results of this thesis, Saskatchewan canola producers appear on average to be applying nitrogen at levels near or below the estimated economic optimal rate.

7.1.3 Nitrogen Application Over Time

Regardless of the nitrogen cost to canola price ratio, there is a strong upward trend of observed nitrogen fertilizer application over time on average. Some potential explanations of reasons why this may be the case include increased capacity equipment for high rates of fertilizer at seeding and increased target yields. One major limitation of nitrogen fertilizer application can be capacity of equipment at seeding. There have been vast improvements in seeding equipment that allow for higher nitrogen fertilizer rates to be applied with greater ease. One potential explanation for increased nitrogen fertilizer rates over time, is that Saskatchewan producers have been adopting this improved seeding technology over the years 2011-2019. Another potential explanation for the strong time trend of increasing nitrogen fertilizer application rates is the increased targets producers and agronomists are setting for expected canola yield. Increasing target yields over time could be a result of a wide range of factors that improve canola yield, including the yield potential of the variety. The yield potential of canola varieties over the years 2011-2019 in Saskatchewan is proxied by the variety index used in this analysis, which shows a strong trend upwards over time. The observed increase in nitrogen applied rates over time by Saskatchewan canola producers may be a response to the improvement of canola varieties over time, with producers upping nitrogen rates to meet the increased yield potential of new varieties.

7.1.4 Environmental Policy Scenarios

From the results of this thesis, Saskatchewan canola producers appear to be applying nitrogen at levels mainly near or below the estimated economic optimal rate. These results indicates that at the aggregate level, producers are not applying excessive rates from an economic perspective. However, exploring policies to reduce emissions is crucial in the face of national targets to reduced GHG emission from nitrogen fertilizer application of 30% by the year 2030 from 2020. One approach to reducing nitrogen fertilizer emissions may be through reduced nitrogen rates.

7.1.5 Nitrogen Fertilizer Application Reduction

This thesis explored the potential effects of reducing nitrogen fertilizer application from the economic optimum on net return and GHG mitigation cost associated with reduced nitrogen rates. A reduction in nitrogen fertilizer applied from the estimated economic optimum resulted in a loss in canola grower's net return. A reduction in nitrogen fertilizer by 20 kg ha^{-1} from the EONR results in a modest loss of net return of \$2.8 - 2.9 ha^{-1} while a reduction in nitrogen fertilizer by 40 kg ha^{-1} from the EONR results in a greater net return loses of \$11.3 - 11.6 ha^{-1}. Policies that reduce nitrogen use at levels near the optimal rate are estimated to be quite modest, however larger reductions in nitrogen applied from the economic optimum will more negatively impact canola producers' net return. The modest losses of net return at even large deviations from the economic optimal level of N supports previous findings of nearly flat pay-off functions for nitrogen in crop production (Pannell, 2017). The cost of GHG mitigation for nitrous oxide emissions from nitrogen application in Canola in the black and brown soil zone was estimated. At a 20 kg ha^{-1} reduction in nitrogen fertilizer from the economic optimum, the GHG mitigation cost is estimated to be \$190 CO_2eq t^{-1} for the brown soil zone and \$92.1 CO_2eq t^{-1} for the black soil zone. At a 40 kg ha^{-1} reduction in nitrogen fertilizer from the economic optimum, the GHG mitigation cost is estimated to be \$381 CO_2eq t^{-1} for the brown soil zone and \$185 CO_2eq t^{-1} for the black soil zone. In the case of producers under-applying nitrogen relative to the economic optimal nitrogen rate, the estimates of the GHG mitigation cost are an under-estimation of the costs of nitrogen fertilizer reduction. Conversely, in the case of producers over-applying nitrogen relative to the economic optimal nitrogen rate, the estimates of the GHG mitigation cost are an over-estimation of the costs of nitrogen fertilizer reduction. To the author's knowledge, there have been no previous studies looking at the marginal abatement cost of nitrous oxide emissions from nitrogen application in canola in Saskatchewan. The estimated reductions in net return and GHG mitigation cost provided in this section aim to fill this gap in current research.

7.1.6 Tax on Nitrous Oxide Emissions

This thesis also examined the potential impact of a tax on nitrous oxide emissions using the Government of Canada's own social cost of carbon. The changes in optimal nitrogen application rates, yield penalties and change in net return were estimated. This study assessed the potential effects of a tax on direct nitrous oxide emissions from nitrogen fertilizer application. The results indicate that this policy could have potential impacts on nitrogen fertilizer use and subsequent net return for Saskatchewan canola producers. When applying the 2030 social cost of carbon (\$170 CO_2eq t^{-1}) and the emissions factor for the black soil zone (0.0033), the added tax to nitrogen would amount to over 20% of the historical average price in 2019 of \$1208 t^{-1} of nitrogen. At the 2030 social cost of carbon, the reduced nitrogen fertilizer applied is estimated to reduce producer net return with loses of \$16.00 – 18.20 ha^{-1} in the brown soil zone and \$32.40 – 36.20 ha^{-1} in the black soil zone using the 2030 social cost of carbon. Under a nitrous oxide tax based on the scheduled 2030 price of carbon the reduction in GHG emissions is estimated as 6.57 – 6.70 kg CO_2 eq ha^{-1} for the brown soil zone and 28.3 – 29.5 kg CO_2 eq ha^{-1}. The changes in optimal nitrogen application rates, yield penalties and change in net return were estimated to provide insight on the potential impact of a N_2O tax.

7.1.7 Comparison of 1) Private Optimum, 2) Social Optimum and 3) 30% Nitrogen Rate Reduction

The private optimum, a tax on N_2O emissions using the Government of Canada's social cost of carbon is applied and a 30% nitrogen fertilizer reduction were compared including an assessment of the welfare effects of each scenario. The estimated welfare effects indicate that for both the current (\$50 CO_2eq t^{-1}) and future social cost of carbon (\$170 CO_2eq $t^{-1}$the policy scenario that results in the greatest overall welfare is the N_2O tax (social optimum). In the privately optimal scenario, the negative externality of pollution from nitrogen fertilizer application reduces overall welfare relative to the social optimum. However, when a policy is imposed to reduce nitrogen fertilizer application rates by 30%, our estimates suggest this is an overly restrictive policy even when using the federal government's highest scheduled carbon price for 2030 of \$170/CO_2eq tonne. This policy would greatly reduce canola producers' welfare as well as create a dead weight loss to society. Applying a tax on nitrous oxide emissions using the governments' own social cost of carbon schedule is estimated to reduce fertilizer use by a rate less than 30% when only accounting for direct emissions. From a socially optimal nitrous oxide tax, fertilization rates are estimated to be reduced by 12.3 – 14.6% in the black soil zone and 6.12 – 6.92% in the brown soil zone from the economic optimum at the 2030 social cost of carbon of \$170 CO_2eq t^{-}. The socially optimal reduction in fertilization rates is estimated to be 3.40 – 4.62% in the black soil zone and 2.04 – 2.31% in the brown soil zone from the economic optimum at the current social cost of carbon of \$50 CO_2eq t^{-1}.

7.1.8 Other Policies to Reduce GHG from Nitrogen Application

One approach to reducing nitrogen fertilizer emissions may be through reduced nitrogen rates. The estimated reductions in net return and GHG mitigation cost provided in this section are a starting point to understanding the potential effects of such policies. It is important to note that according to the estimates of the economic optimal nitrogen applied rate in this thesis, producers appear to currently on average be applying nitrogen near or below the economic optimal nitrogen rate. Therefore, policies aimed at the other 4R's of Nutrient Stewardship may be more favourable to reduce emissions from nitrogen fertilizer. Focusing on agronomic research, extension, and policy to improve nitrogen management and optimize fertilizer use, are other opportunities to reduce emissions. The 4R's of Nutrient Stewardship are the right source at the right rate, right time, and right place. The federal government has stated the main policy focus will not be a mandatory reduction in the use of fertilizers, but instead on improving nitrogen management and optimizing fertilizer use. The best nutrient management practices encompassed in Fertilizer Canada's 4R approach are highlighted by the federal government as providing opportunities to reduce fertilizer emissions and improve nitrogen use efficiency. Other specific best practices named by the federal government include use of enhanced efficiency fertilizers, minimizing fall application and broadcasting of fertilizer, annual soil testing and increased use of pulse crops (Government of Canada, 2022).

One circumstance where Saskatchewan producers may be able to reduce nitrogen fertilizer rate based on the results of this study is in the case of canola following pulse crops. The yield model estimates that producers growing canola on pulse previous crop have significantly lower economic optimal nitrogen rates. From the observed application rates of nitrogen, producers on aggregate appear to not be varying nitrogen application rates by previous crop. Canola fields grown on pulse previous crop is the only instance in the results where the observed mean is sometimes over the estimated economic optimal rate. However, there may be limited potential to reduce nitrogen application overall as a small relative percentage of canola fields were grown on pulse previous crop in the sample (~9.7%) with some Risk Zones in the sample having significantly smaller proportion of pulse acres (ex. RZ = 14, 17). Reasons for low seeded area of pulse crops may be due to agronomic pressures such as disease or weather pressures such as too much average growing season precipitation. Another potential reason for low pulse area may be due to economic considerations of producers.

7.2 Limitations of the study

7.2.1 Limitations of Data & Estimation of Production Function

There are important limitations to note in the data availability and the resulting methodology chosen in estimating the canola production function. This study was based on producer provided records for Saskatchewan Crop Insurance Corporation under the Saskatchewan Management Plus Program. While this data set is rich in observations and contains a wide spatial range of producers, this data and resulting analysis is subject to the accurate reporting of producers and thus may be biased in the case of inaccurate reporting. There is also potential for selection bias as the data used in analysis is based on producers who are enrolled in the SMP program and who also vary N rates by field within a year. The estimates from the canola production are also limited by the potential for bias in the case of correlation between input levels and unobserved time-varying producer-specific shocks. Producer fixed effects were used in the estimation of the canola production function model to control for the variation in canola yields that vary by producers that is otherwise unobserved (such as managerial ability). However, the use of fixed effects does not address productivity shocks that are not fixed over time, in which case the estimates of this production function may be biased. While alternative methods using either an investment proxy or intermediate input proxy variable have been found to address this simultaneity problem, these alternative methods were not used due to a lack of available data on producer-level investment (Levinsohn & Petrin, 2003). The estimation of the economic optimal nitrogen application rate was derived using average annual prices and an aggregated canola response function. In reality, individual producers will have differing economic optimal nitrogen application rates based on individual risk aversion, nitrogen prices, canola prices, transportation costs and canola yields that are a function of a variety of variable inputs management and climatic factors that are specific to an individual producer. Another limitation of this study is that the estimation of the canola nitrogen response curve was based on the reported nitrogen applied rate without data on soil available nitrogen which is an important factor in the canola nitrogen response curve.

7.2.2 Limitations in Emissions Estimates

The emissions from nitrogen fertilizer application considered in this study were direct emissions. However, there are other GHG emissions associated with nitrogen fertilizer that are important considerations that were not the focus of this study. The greenhouse gas emissions associated with indirect emissions, namely leaching, and ammonification, could be included in future works to develop of a more complete GHG cost abatement curve for nitrogen application in Saskatchewan. For the purposes of this study, an aggregate emissions factor was used at the black and brown soil zone ecoregion level. In reality, the individual nitrogen fertilizer practices of a producer can greatly impact the precise emissions factor as well as nitrogen use efficiency. The timing of nitrogen application, the product used, and placement are all important factors that affect nitrous oxide emissions and nitrogen use efficiency. Unfortunately, information on these important factors was not available at the producer level and thus this study is limited in providing a disaggregated estimate of direct nitrous oxide emissions. In assessing the impact of any environmental policy, the effects on the intensive and extensive margins should be considered. One potential effect of a tax on nitrogen application or reduced nitrogen fertilizer use in Saskatchewan canola is a change in the acreage allocation of Saskatchewan producers. One might hypothesis that producers may substitute acres to less nitrogen intensive crops, such as pulses. These are important considerations that were beyond the scope of this thesis that would be interesting questions to be investigated in future research.

7.3 Areas of further research

7.3.1 Follow up with a survey on producer nitrogen fertilizer practices

One area of further research that is suggested is a survey of producers in the SMP program of Saskatchewan Crop Insurance. A survey of SMP producers could serve to supplement the rich data set used in this thesis with more detailed information on producers’ perceptions and practices associated with fertilizer use and practices. This additional information could be used to further understand nitrogen fertilizer practices by Saskatchewan producers as well as create a better understanding of the best potential areas for policies to reduce nitrous oxide emissions.

7.3.2 Lack of global uniform environmental policy

The global impacts of any environmental policy need to be considered. Environmental policies that impact Saskatchewan canola production also have potential far reaching impacts globally. Environmental policies that reduce canola production in Saskatchewan could potentially increase production in other areas of the world to increase to meet the gap in vegetable oil production. Pollution havens are an important consideration in the absence of a globally uniform environmental policy. Thus, further research in this area is needed on the global impacts of Canadian domestic emissions policy on nitrogen fertilizer is needed.

7.3.3 A note on GHG IPCC Accounting System

The GHG accounting system used for this thesis followed the system outlined by the IPCC. This accounting system was chosen based on its use for assessing compliance with carbon commitments in the Kyoto protocol as well as the Canadian federal government's National Inventory (Environment and Climate Change Canada, 2018). Further policy research in the area of GHG emission associated with production of canola in Saskatchewan will be required in the future as policy makers aim to meet Canada's international climate commitments. The IPCC accounting system is a useful tool and guideline for future researchers. However, the use of the IPCC accounting system is not without limitations which have been explored in previous literature, particularly in the case of biofuels. Searchinger et al., (2009) outlines crucial climate accounting errors in the IPCC method, where in the case of biofuels two main areas of emissions are not accounted for: 1) CO_2 emitted from tailpipes and smokestacks when bioenergy is being used 2) Changes in emissions from land used when biomass for energy is harvested or grown (Searchinger, et al., 2009). These are important considerations for future research in the area of GHG accounting in the case of biofuels such as canola.

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APPENDIX A

Table A.1 Variety by variety index, average yield in sample, age, number of observations and percent of observations in sample.

Variety Name	Variety Index	Average Yield	Variety Age	Number of Observations	% of Observations
11DL30318	44.1	1121.9	5.2	1	0.002
3950 SW	48.5	1233.1	14.0	2	0.004
4424 RR	48.5	1233.1	10.9	1	0.002
INDEPENDENCE	49.6	1261.5	23.3	4	0.008
4414 RR	51.1	1298.7	12.4	7	0.015
WIZZARD SW	53.9	1370.2	16.0	2	0.004
4434 RR	54.0	1373.0	10.9	8	0.017
44A53	54.7	1390.7	18.9	3	0.006
401 HYOLA	55.1	1401.1	27.9	3	0.006
4362 RR	55.1	1401.1	12.4	5	0.011
6130	57.3	1456.7	9.6	2	0.004
BARRIER VT	58.9	1497.2	10.7	48	0.102
46A65	58.9	1498.7	23.1	8	0.017
5070 INVIGOR	59.0	1499.3	15.7	4	0.008
32-35 DKL	61.7	1569.1	20.1	4	0.008
L170S	61.7	1569.1	22.7	2	0.004
73-35	61.9	1573.3	8.0	13	0.028
34-65	62.9	1600.1	14.1	17	0.036
71-40 CL	63.0	1600.4	11.1	6	0.013
3303 LL	63.5	1613.6	12.3	2	0.004
1841	64.0	1626.0	17.0	1	0.002
72-35 RR	64.6	1643.2	10.3	1	0.002
94H04	65.0	1653.3	8.8	23	0.049
72-55 RR	65.8	1672.4	11.1	16	0.034
DESIRABLE RR SP	65.9	1674.8	14.9	16	0.034
1960	66.1	1680.3	9.1	3	0.006
45H20	66.1	1680.3	18.1	1	0.002
46H23	66.1	1680.3	16.1	1	0.002
601	66.1	1680.3	18.9	1	0.002
9551	66.1	1680.3	13.1	1	0.002
BULLET DEREGISTERED	66.1	1680.3	25.1	1	0.002
EXCEL AC	66.1	1680.3	29.0	6	0.013
SP BUCKY	66.1	1681.5	17.0	2	0.004
1818	66.2	1683.8	14.4	22	0.047
REMARKABLE VT	67.0	1704.5	9.7	120	0.255

46P50	67.2	1708.4	13.0	21	0.045
4.30E+03	68.6	1744.6	7.1	8	0.017
9350	68.9	1751.2	10.1	12	0.025
6802 SW	69.0	1754.4	14.8	1	0.002
9550	70.3	1787.8	15.7	10	0.021
1980 CANTERRA	70.5	1793.1	7.7	8	0.017
43H57	71.1	1808.6	12.0	11	0.023
9555	71.4	1814.1	9.7	8	0.017
45S53	71.5	1817.3	8.1	26	0.055
RUGBY	71.7	1823.5	12.0	15	0.032
4.30E+02	71.8	1824.9	11.1	18	0.038
45A71	71.8	1826.6	22.2	5	0.011
45H26	71.9	1829.0	13.0	28	0.059
74-47	72.0	1830.2	6.4	3	0.006
1855H	72.7	1848.3	12.0	2	0.004
46A76	73.7	1873.8	20.0	44	0.093
9553	73.7	1874.1	11.1	168	0.357
500 VT	74.2	1887.5	22.1	643	1.366
997 RR	74.3	1888.6	12.4	14	0.030
73-45	74.4	1892.7	9.1	663	1.409
621 RR SP	74.6	1896.1	12.4	6	0.013
3150 D	75.5	1918.4	11.1	50	0.106
71-45	75.6	1921.6	13.8	14	0.030
45A51	75.7	1923.7	21.1	4	0.008
73-65	75.7	1924.8	9.1	47	0.100
6040	75.8	1926.5	9.6	42	0.089
3151 D	75.9	1929.3	11.1	108	0.229
45H25	76.4	1942.2	14.1	3	0.006
46S53	77.0	1956.5	8.1	73	0.155
73-75 RR	77.0	1958.2	8.0	322	0.684
73-15 RR	77.1	1959.8	8.0	49	0.104
BANNER	77.1	1961.2	17.0	3	0.006
46H70	77.2	1962.0	15.1	1	0.002
72-65	77.4	1967.5	10.1	317	0.674
73-55	77.6	1971.8	9.1	88	0.187
45H74	77.7	1975.5	9.1	57	0.121
1849	77.7	1975.6	16.8	2	0.004
L135C	78.2	1989.0	6.7	14	0.030
46M34	78.5	1995.7	4.1	89	0.189
1950 CANTERRA	78.7	2001.3	9.8	17	0.036
74-54 RR	79.1	2011.7	5.9	211	0.448
5770 INVIGOR	79.4	2018.2	9.8	232	0.493
4135SY	79.8	2028.5	6.3	36	0.076

1852H	79.8	2029.2	13.0	5	0.011
FOREMOST	80.4	2044.8	20.0	2	0.004
6020	80.5	2046.5	9.6	11	0.023
3156M D	80.8	2053.6	2.0	32	0.068
1970	80.8	2053.7	8.7	76	0.161
9559 PROVEN VR	81.1	2061.7	8.1	275	0.584
45H29	81.3	2067.2	8.9	1308	2.779
2473 INVIGOR	81.5	2073.2	20.1	1	0.002
45A50	81.5	2073.2	21.1	6	0.013
5020 INVIGOR	81.6	2075.0	15.7	58	0.123
45H28	81.7	2078.2	11.1	46	0.098
1918	82.0	2083.8	8.5	94	0.200
45P70	82.6	2099.6	13.0	45	0.096
5535 CL	82.6	2101.0	8.7	71	0.151
1024 RR	82.7	2101.6	2.0	2	0.004
L150	83.0	2110.7	8.6	2369	5.034
6060	83.3	2117.1	8.7	466	0.990
45S52	83.3	2117.5	9.0	162	0.344
CLAVET	83.8	2130.0	23.0	1	0.002
9557S	84.0	2136.4	9.1	41	0.087
4114SY	84.1	2137.5	6.1	3	0.006
35-25 DKL	84.2	2141.9	19.0	9	0.019
2200 CS CL	84.3	2143.8	3.9	7	0.015
32-75	84.5	2148.2	15.0	3	0.006
45M38	84.7	2154.6	2.0	27	0.057
L120	85.3	2167.8	7.7	418	0.888
2463 INVIGOR	85.3	2167.9	20.1	21	0.045
2563 INVIGOR	86.0	2185.6	19.1	2	0.004
73-77	86.0	2185.6	9.1	2	0.004
2600 CS CR-T	86.0	2185.7	1.2	13	0.028
500 OPTION	86.0	2186.3	22.1	4	0.008
45S51	86.1	2189.1	10.9	45	0.096
9561 VR GS	86.3	2194.8	6.1	10	0.021
8440 INVIGOR	86.4	2197.5	12.0	245	0.521
560 PV GM	86.5	2200.1	3.0	23	0.049
45H73	86.6	2201.7	13.0	89	0.189
5030 INVIGOR	86.6	2202.4	15.7	126	0.268
6044 RR	86.8	2206.0	5.8	25	0.053
644 LBD RR	87.1	2214.1	16.1	1	0.002
644 RR	87.1	2214.1	16.1	1	0.002
L160S	87.5	2224.4	5.9	56	0.119
1956 CANTERRA	88.2	2241.2	9.6	2	0.004
9554	88.2	2241.2	10.8	1	0.002

9590	88.3	2244.2	12.9	58	0.123
2400 CS	88.7	2254.4	1.0	9	0.019
3153 D	88.7	2255.8	8.1	338	0.718
1826 RR	89.1	2266.3	13.3	7	0.015
L159	89.3	2270.5	7.5	584	1.241
C5507	89.3	2270.9	2.0	1	0.002
34-55	89.5	2275.3	19.0	5	0.011
1990 CANTERRA	89.6	2278.1	7.9	491	1.043
74-44	89.7	2280.9	6.4	1630	3.464
5525 CL	89.8	2282.0	9.8	273	0.580
3154S D	90.0	2287.4	7.1	77	0.164
9560 CL	90.3	2294.7	8.1	192	0.408
531PV G	90.4	2297.9	3.6	11	0.023
532PV G	90.4	2298.1	5.1	1	0.002
5440 INVIGOR	90.5	2301.6	12.0	5616	11.934
2000 CS	90.6	2303.6	3.0	92	0.195
4.30E+04	90.6	2303.8	5.1	38	0.081
1492 CANTERRA	90.7	2305.5	20.1	7	0.015
4166SY	90.9	2310.6	3.8	12	0.025
L154	91.0	2313.7	7.5	269	0.572
533PV G	91.2	2317.5	3.6	105	0.223
530 VT	91.3	2322.0	6.1	294	0.625
45H75	91.6	2329.0	9.1	146	0.310
45S54	91.9	2335.3	7.1	405	0.861
45H31	92.0	2339.3	8.1	978	2.078
2100 CS	92.0	2339.7	4.0	34	0.072
6050 RR	92.4	2350.0	6.6	6	0.013
1851 CANTERRA	92.6	2354.9	14.0	1	0.002
46A74	92.6	2354.9	21.1	2	0.004
590 GCS PV	93.3	2373.2	3.1	5	0.011
540PV G	93.4	2374.1	2.9	442	0.939
L130	93.6	2379.3	8.6	5267	11.192
93H01 RR	93.7	2382.1	11.7	2	0.004
9552	93.9	2388.0	10.7	10	0.021
200PV CL	94.3	2397.9	4.1	117	0.249
530PV G	94.5	2402.4	6.1	185	0.393
3152 D	94.8	2410.5	9.1	2	0.004
DKTF 94 CR	95.3	2422.4	0.9	38	0.081
45H21	95.4	2425.9	17.1	7	0.015
L140P	96.1	2442.6	5.9	2133	4.533
75-65 RR	96.8	2461.3	3.8	658	1.398
9562 VR GC	97.0	2465.5	6.1	110	0.234
510 VT	97.0	2466.1	7.8	1	0.002

75-45 RR	97.3	2474.0	4.0	280	0.595
45CM36	97.4	2477.4	2.1	28	0.059
L261	98.4	2501.8	5.9	339	0.720
68 K	98.5	2503.2	2.0	3	0.006
6090 RR	99.0	2516.3	1.0	76	0.161
45CS40	99.1	2519.1	3.1	343	0.729
45H24	99.2	2522.9	15.1	1	0.002
45H72	99.2	2522.9	15.0	1	0.002
811 RR	99.2	2522.9	17.0	1	0.002
PV 760 TM	99.2	2522.9	1.2	1	0.002
PV 780 TC	99.2	2522.9	0.3	2	0.004
3155C D	99.3	2525.1	5.1	158	0.336
46H75	99.4	2527.6	8.1	652	1.385
5545 CL	99.6	2532.4	2.9	93	0.198
45M35	99.6	2532.5	3.1	399	0.848
DKTF 92 SC	99.7	2535.7	0.9	45	0.096
581PV GC	99.8	2537.0	3.0	36	0.076
L252	100.0	2542.3	5.9	6117	12.999
45H37	100.2	2546.2	5.1	7	0.015
DKLL 81 BL	100.5	2555.5	1.9	27	0.057
45H33	100.8	2562.7	5.1	728	1.547
1999	101.0	2566.9	6.4	5	0.011
45H76	101.3	2574.2	5.1	202	0.429
73-67	101.4	2577.3	9.1	3	0.006
4157SY	103.5	2632.4	5.9	42	0.089
6080 RR	104.0	2643.3	3.1	38	0.081
75-42 CR	104.3	2652.5	0.2	21	0.045
45S56	104.4	2654.9	5.1	172	0.365
6074 RR	104.5	2656.0	3.1	518	1.101
6056 CR	104.5	2657.6	6.9	14	0.030
6064 RR	104.5	2657.8	5.2	33	0.070
L230	105.2	2674.0	2.9	1318	2.801
P501L	106.2	2699.8	0.5	59	0.125
9440	106.3	2701.8	18.0	5	0.011
2300 CS	107.2	2725.0	1.9	47	0.100
501 OPTION	107.5	2731.7	0.5	8	0.017
L233P	107.5	2733.1	2.9	3843	8.166
45CM39	109.7	2788.1	1.1	144	0.306
L255PC	109.8	2790.8	1.0	349	0.742
2733 INVIGOR	110.2	2802.2	18.1	4	0.008
L234PC	112.1	2848.8	0.1	110	0.234
23-38 DKL	112.4	2857.8	19.0	6	0.013
L241C	114.6	2912.3	3.7	88	0.187

591PV GCS	114.6	2913.4	1.0	1	0.002
580PV GC	120.5	3063.3	3.5	3	0.006
PV 680 LC	120.7	3067.4	0.5	17	0.036
ALLONS	125.7	3195.1	24.5	1	0.002
DYNAMITE OAC	129.6	3295.4	22.1	5	0.011
5505 CL	132.3	3363.1	11.8	1	0.002
LEGACY	132.3	3363.1	26.1	1	0.002
585PV GC	133.1	3384.4	0.0	5	0.011

APPENDIX B

Table B.1 Producer fixed effects model version versus management index variable model version.

	Producer FE	**Management Index**
Nitrogen	1.86 (1.81)	−6.293 (0.860)***
Nitrogen^2	−0.0140 (0.00535)**	−0.013 (0.002)***
Phosphorous	2.34 (1.02)*	1.178 (0.219)***
Potassium	3.36 (1.18)**	1.866 (0.246)***
Sulphur	2.77 (0.973)**	1.222 (0.229)***
Variety Index	4.65 (2.31)*	−3.451 (1.542)*
Liberty Link Dummy	529 (155)***	509.150 (118.842)***
Roundup Ready Dummy	419 (153)**	262.122 (117.490)*
Average Precipitation	1.86 (0.771)*	0.523 (0.300)+
Average Precipitaiton^2	−0.00272 (0.00142)+	−0.001 (0.001)*
GS Precipitation	0.469 (0.352)	2.964 (0.146)***
GS Precipitation^2	−0.00128 (0.00065)*	−0.006 (0.000)***
Seeding Date	4.79 (1.30)***	0.187 (0.568)
Seeding Date^2	−0.376 (0.0691)***	−0.182 (0.025)***
Fungicide Dummy	152 (9.01)***	150.514 (4.286)***
Cereal Previous crop Dummy	21.5 (19.7)	−15.219 (19.211)
Pulse Previous crop Dummy	63.9 (29.5)*	54.832 (31.490)+
Variety Index x Liberty Link Dummy	−4.91 (1.63)**	−5.038 (1.260)***
Variety Index x Roundup Ready Dummy	−4.26 (1.61)**	−2.810 (1.251)*
Nitrogen x Cereal Previous crop Dummy	−0.155 (0.176)	−0.036 (0.174)
Nitrogen x Pulse Previous crop Dummy	−0.482 (0.268)+	−0.402 (0.287)
N x Variety Index	0.0444 (0.0155)**	0.133 (0.009)***
Management Index		11.473 (0.190)***
R2	0.038	0.499
R2 Adj.	0.853	0.498
R2 Within	0.803	0.255
Std.Errors	Hetero-robust	Hetero-robust
Producer fixed effects	X	
Producer * Year fixed effects	X	
Year fixed effects	X	X
Risk zone fixed effects	X	X
Soil class fixed effects	X	X

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table B.2 Final model version versus variety index model versions versus variety fixed effects model.

	Final Model	**Variety Index**	**Variety FE**
Nitrogen	1.86 (1.81)	5.300 (1.288)***	4.996 (1.246)***
Nitrogen^2	−0.0140 (0.00535)**	−0.012 (0.005)*	−0.010 (0.005)*
Phosphorous	2.34 (1.02)*	2.373 (0.975)*	1.944 (0.955)*
Potassium	3.36 (1.18)**	3.385 (1.137)**	3.260 (1.133)**
Sulphur	2.77 (0.973)**	2.904 (0.933)**	3.076 (0.889)***
Variety Index	4.65 (2.31)*	5.205 (0.408)***	
Liberty Link Dummy	529 (155)***	63.683 (11.394)***	
Roundup Ready Dummy	419 (153)**	17.157 (11.852)	
Average Precipitation	1.86 (0.771)*	1.879 (0.740)*	1.676 (0.738)*
Average Precipitaiton^2	−0.00272 (0.00142)+	−0.003 (0.001)*	−0.002 (0.001)+
GS Precipitation	0.469 (0.352)	0.467 (0.340)	0.415 (0.338)
GS Precipitation^2	−0.00128 (0.00065)*	−0.001 (0.001)*	−0.001 (0.001)+
Seeding Date	4.79 (1.30)***	4.760 (1.254)***	4.558 (1.240)***
Seeding Date^2	−0.376 (0.0691)***	−0.373 (0.067)***	−0.358 (0.066)***
Fungicide Dummy	152 (9.01)***	152.338 (8.665)***	151.212 (8.686)***
Cereal Previous crop Dummy	21.5 (19.7)	4.397 (4.291)	5.496 (4.255)
Pulse Previous crop Dummy	63.9 (29.5)*	10.646 (6.436)+	11.961 (6.402)+
Variety Index x Liberty Link Dummy	−4.91 (1.63)**		
Variety Index x Roundup Ready Dummy	−4.26 (1.61)**		
Nitrogen x Cereal Previous crop	−0.155 (0.176)		
Nitrogen x Pulse Previous crop	−0.482 (0.268)+		
N x Variety Index	0.0444 (0.0155)**		
R2	0.853	0.853	0.856
R2 Adj.	0.803	0.803	0.806
R2 Within	0.038	0.037	0.022
Std.Errors	Hetero-robust	Hetero-robust	Hetero-robust
Producer fixed effects	X	X	X
Producer * Year fixed effects	X	X	X
Year fixed effects	X	X	X
Risk zone fixed effects	X	X	X
Soil class fixed effects	X	X	X
Variety Fixed Effects			X

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table B.3 Estimated optimal nitrogen application rate by previous crop and annual average cost ratios with variety index at the annual sample mean using Model 6 as shown in Table 5-3 with soil, producer, and year x RZ fixed effects.

Year	Canola Price ($/ tonne)	N Cost ($/tonne)	Variety Index (% of L252)	Cost Ratio	EONR (kg ha^{-1})	St. Error	Obs. Mean N Rate (kg/ha)
			Oilseed Previous crop				
2011	$478	1158	83.5	2.42	68.8	13.5	98*
2012	$461	1390	84.3	3.02	46.8	17.9	99*
2013	$529	1352	87.1	2.56	77	11.9	104*
2014	$432	1287	90.1	2.98	71.3	13	107*
2015	$418	1309	93.2	3.13	77.2	12	106*
2016	$446	1195	95.6	2.68	105	8.1	111
2017	$466	1061	97.6	2.27	130	8.4	117*
2018	$501	1035	101.6	2.07	154	11.9	120*
2019	$511	1208	103.9	2.36	151	11.4	121*
			Cereal Previous crop				
2011	$478	1158	83.5	2.42	63.5	13.6	97*
2012	$461	1390	84.3	3.02	41.6	18.3	99*
2013	$529	1352	87.1	2.56	71.8	12	103*
2014	$432	1287	90.1	2.98	66	13.3	104*
2015	$418	1309	93.2	3.13	71.9	12.3	108*
2016	$446	1195	95.6	2.68	100.2	7.7	111*
2017	$466	1061	97.6	2.27	125.2	7.2	113*
2018	$501	1035	101.6	2.07	149.3	10.6	118*
2019	$511	1208	103.9	2.36	146.2	10.2	119*
			Pulse previous crop				
2011	$478	1158	83.5	2.42	63.9	16.4	100*
2012	$461	1390	84.3	3.02	42	20.6	98*
2013	$529	1352	87.1	2.56	72.2	15	106*
2014	$432	1287	90.1	2.98	66.4	16.1	108*
2015	$418	1309	93.2	3.13	72.3	15.2	108*
2016	$446	1195	95.6	2.68	100.6	11.5	110
2017	$466	1061	97.6	2.27	125.6	11	112*
2018	$501	1035	101.6	2.07	149.7	13.2	116*
2019	$511	1208	103.9	2.36	146.6	12.9	118*

*indicates that the observed mean rate is outside of the EONR st.errors

Table B.4 Estimated optimal nitrogen application rate by previous crop and annual average cost ratios with variety index at the annual sample mean using the Management Index Model shown in Table B.1.

Year	Canola Price ($/ tonne)	N Cost ($/tonne)	Variety Index (% of L252)	Cost Ratio	EONR (kg ha^{-1})	St. Error	Obs. Mean N Rate (kg/ha)
Oilseed Previous crop							
2011	$478	1158	83.5	2.42	91.6	7.3	98
2012	$461	1390	84.3	3.02	72.8	9.0	99
2013	$529	1352	87.1	2.56	104.6	6.4	104
2014	$432	1287	90.1	2.98	103.8	6.1	107
2015	$418	1309	93.2	3.13	113.8	5.9	106
2016	$446	1195	95.6	2.68	143.1	8.2	111
2017	$466	1061	97.6	2.27	168.9	11.8	117
2018	$501	1035	101.6	2.07	196.8	16.1	120
2019	$511	1208	103.9	2.36	197.4	16.1	121
Cereal Previous crop							
2011	$478	1158	83.5	2.42	90.3	6.0	97
2012	$461	1390	84.3	3.02	71.5	8.1	99
2013	$529	1352	87.1	2.56	103.2	4.9	103
2014	$432	1287	90.1	2.98	102.4	4.8	104
2015	$418	1309	93.2	3.13	112.4	4.6	108
2016	$446	1195	95.6	2.68	141.8	7.1	111
2017	$466	1061	97.6	2.27	167.5	11.0	113
2018	$501	1035	101.6	2.07	195.4	15.5	118
2019	$511	1208	103.9	2.36	196.1	15.5	119
Pulse previous crop							
2011	$478	1158	83.5	2.42	76.3	11.9	100
2012	$461	1390	84.3	3.02	57.5	13.8	98
2013	$529	1352	87.1	2.56	89.3	10.8	106
2014	$432	1287	90.1	2.98	88.5	10.8	108
2015	$418	1309	93.2	3.13	98.5	10.3	108
2016	$446	1195	95.6	2.68	127.8	10.2	110
2017	$466	1061	97.6	2.27	153.6	12.2	112
2018	$501	1035	101.6	2.07	181.5	15.5	116
2019	$511	1208	103.9	2.36	182.1	15.5	118

Table B.5 Estimated optimal nitrogen application rate by previous crop and annual average cost ratios with variety index at the annual sample mean using Model 5 in Table 5-3 with soil, RZ, year and producer fixed effects.

Year	Canola Price ($/ tonne)	N Cost ($/tonne)	Variety Index (% of L252)	Cost Ratio	EONR (kg ha^{-1})	St. Error	Obs. Mean N Rate (kg/ha)
			Oilseed Previous crop				
2011	$478	1158	83.5	2.42	38.5	28.8	98
2012	$461	1390	84.3	3.02	8.5	38.9	99
2013	$529	1352	87.1	2.56	57.6	22.9	104
2014	$432	1287	90.1	2.98	55.3	23.8	107
2015	$418	1309	93.2	3.13	70.0	19.6	106
2016	$446	1195	95.6	2.68	115.4	11.4	111
2017	$466	1061	97.6	2.27	155.4	18.2	117
2018	$501	1035	101.6	2.07	198.0	31.2	120
2019	$511	1208	103.9	2.36	198.2	31.1	121
			Cereal Previous crop				
2011	$478	1158	83.5	2.42	32.05	29.90	97
2012	$461	1390	84.3	3.02	2.07	40.25	99
2013	$529	1352	87.1	2.56	51.17	23.83	103
2014	$432	1287	90.1	2.98	48.85	24.91	104
2015	$418	1309	93.2	3.13	63.54	20.56	108
2016	$446	1195	95.6	2.68	108.98	10.15	111
2017	$466	1061	97.6	2.27	148.95	15.78	113
2018	$501	1035	101.6	2.07	191.58	28.93	118
2019	$511	1208	103.9	2.36	191.73	28.85	119
			Pulse previous crop				
2011	$478	1158	83.5	2.42	38.8	31.2	100
2012	$461	1390	84.3	3.02	8.8	40.7	98
2013	$529	1352	87.1	2.56	57.9	25.8	106
2014	$432	1287	90.1	2.98	55.6	26.7	108
2015	$418	1309	93.2	3.13	70.3	23.1	108
2016	$446	1195	95.6	2.68	115.7	16.5	110
2017	$466	1061	97.6	2.27	155.7	21.6	112
2018	$501	1035	101.6	2.07	198.3	33.3	116
2019	$511	1208	103.9	2.36	198.5	33.2	118

Table B.6 Estimated optimal nitrogen rate by previous crop and a range of canola prices and nitrogen costs and the average mean variety index over the years 2011-2019 in the data set of 93.3% of L252.

			Oilseed Previous crop		**Cereal Previous crop**		**Pulse Previous crop**	
Canola Price ($/tonne)	**N Cost ($tonne)**	**Cost Ratio**	**EONR (kgha^{-1})**	**St. Error**	**EONR (kgha^{-1})**	**St. Error**	**EONR (kgha^{-1})**	**St. Error**
$ 400	$ 1,000	2.50	126	15.01	120	14.17	109	16.50
$ 400	$ 1,250	3.13	104	16.01	98	16.52	87	20.60
$ 400	$ 1,500	3.75	82	20.70	76	22.05	65	26.75
$ 400	$ 1,700	4.25	64	25.89	58	27.57	47	32.45
$ 500	$ 1,000	2.00	144	17.44	138	15.71	127	15.98
$ 500	$ 1,250	2.50	126	15.01	120	14.17	109	16.50
$ 500	$ 1,500	3.00	108	15.43	103	15.69	91	19.52
$ 500	$ 1,700	3.40	94	17.72	89	18.67	77	23.10
$ 600	$ 1,000	1.67	155	20.16	150	18.09	138	17.16
$ 600	$ 1,250	2.08	141	16.90	135	15.27	124	15.87
$ 600	$ 1,500	2.50	126	15.01	120	14.17	109	16.50
$ 600	$ 1,700	2.83	114	14.95	109	14.85	97	18.27
$ 700	$ 1,000	1.43	164	22.49	158	20.27	147	18.65
$ 700	$ 1,250	1.79	151	19.10	146	17.13	134	16.60
$ 700	$ 1,500	2.14	139	16.52	133	14.99	122	15.84
$ 700	$ 1,700	2.43	129	15.20	123	14.20	111	16.26