THE ADOPTION OF SEMIDWARF SPRING WHEAT AND THE ASSOCIATED NITROUS OXIDE EFFECTS IN SASKATCHEWAN

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ABSTRACT

After the Green Revolution, semidwarf varieties of wheat increased in popularity worldwide. With an increase in lodging resistance and higher responsiveness to nitrogen, farmers have the ability to apply more nitrogen to achieve higher yields. However, while semidwarf varieties are favorable to farmers seeking to increase productivity, the net change in greenhouse gas emissions resulting from the increased use of nitrogen fertilizer remains underexplored. This thesis studies the joint determination of semidwarf variety selection and nitrogen use in Saskatchewan, Canada—one of the leading provinces in wheat production. We develop a Control Function (CF) model to estimate the joint choices of semidwarf wheat varieties and nitrogen application rates using field-level data of Saskatchewan farms between 2011 and 2019. After that, we employ emission factors from the literature to estimate changes in direct nitrous oxide (N_2O) emissions when farmers adopt semidwarf wheat and subsequently change nitrogen rates. Our regression model suggests a 5.9% expected increase in nitrogen application rate when a farmer switches from conventional to semidwarf wheat. The subsequent analysis suggests that although semidwarf wheat generally has higher nitrogen application rates than conventional wheat, their fertilizer-induced direct N_2O emissions per tonne of grain production are fairly similar. Based on the adoption status of semidwarf wheat and conventional wheat in 2019, if all conventional wheat acres in Saskatchewan switch to semidwarf wheat, the value of environmen-

tal damage associated with the direct N_2O emissions induced by nitrogen fertilizer applied to Saskatchewan spring wheat would increase by at least \$0.29 millions of CAD.

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DEDICATION

To my parents, Feng and Heli, who always want the best for their son.

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Chapter 1

Introduction

Past works have investigated the driving forces and impacts of adopting improved wheat varieties. Evidence has been provided in several studies that farmers choose varieties to grow based on expected profit, disease and climate resistance, and risk aversion (e.g., Traxler and Byerlee 1993, Heisey et al. 1997, Feder 1980). Nevertheless, the environmental externalities were often overlooked by both producers and researchers in evaluations of the social-economic impact of wheat varieties. The agricultural sector has become a significant contributor to global warming, which is tightly connected to greenhouse gases (GHGs) emissions. The World Resources Institute (2020) reported that agriculture and forestry industries together contributed to nearly 18% of the total 49.2Gt CO_2eq (carbon dioxide equivalent) of global GHGs emissions worldwide in 2016.

A significant portion of GHGs in agriculture can be attributed to nitrogen (N) fertilizer. The application of N fertilizer is a source of nitrous oxide (N_2O) (Zhou et al. 2016), which accounts for 14-23% of the atmospheric N_2O budget (Watson et al. 1992). In Canada, the crop and livestock sector was responsible for 56 million tonnes of CO_2eq of GHGs emissions in 2009, and N_2O accounted for one-third of this number (Agriculture and Agri-food Canada 2020). What makes N_2O a GHG that is worth investigating is that it has nearly 300 times the warming potential compared to CO_2. With the establishment of the Paris Accord, countries are setting up ambitious goals of reducing emissions. As of today, Canada's target is to reduce its GHG emissions by $40-45\%$ below 2005 levels by 2030 (ECCC 2021a). With the deadline approaching, tackling the emission issue is becoming increasingly urgent. The agricultural sector, as one of the pillar industries of Canada's economy, has the potential and responsibility to mitigate its GHG emissions.

Among improved wheat varieties, a collection of varieties called the semidwarf wheat is becoming increasingly popular among farmers. Semidwarf wheat refers to varieties that carry semidwarf genes. The advantages of semidwarf wheat compared to conventional wheat varieties include lodging resistance, nitrogen tolerance, and nitrogen responsiveness. Semidwarf wheat became available to Canadian producers in the late 1960s. Some of these varieties showed significantly higher yields compared to conventional (non-semidwarf) varieties but also lower end-use quality (e.g., low protein content) (McCallum and DePauw 2008). In recent years, popular semidwarf varieties including

Brandon, Lilian, and Utmost expressed dominance in terms of seeded acres in Saskatchewan (Yield Saskatchewan 2019). A more detailed survey of semidwarf wheat is provided in the literature review section. Given that semidwarf wheat responds to nitrogen differently than conventional varieties, farmers may adjust the quantities of nitrogen fertilizer used in their fields based on the varieties chosen, and thus causing the amount of N_2O emitted to vary regionally. To understand the importance of variety selection in GHG emissions in the agricultural sector, this study aims to analyze the effect of adopting semidwarf wheat varieties on nitrogen application rates and to quantify the N_2O emissions induced by changes in nitrogen inputs.

Given the insufficiency in evidence suggesting that semidwarf and conventional wheat varieties emit N_2O differently, this study focuses on the soil direct N_2O emission induced by nitrogen applications. Therefore, direct emissions from sources other than nitrogen applications and indirect emissions are not within the scope of this study. The tasks of this study are to examine (1) factors that determine the probability of a farmer choosing semidwarf wheat relative to conventional wheat, (2) how does the first choice affect a farmer's subsequent choice of nitrogen application rate, and (3) changes in direct N_2O emissions due to different nitrogen application rates.

We use two separate equations to represent the choice of semidwarf wheat and the nitrogen application rate. The fact that these two decisions usually affect each other generates a system of simultaneous equations, introducing simultaneity bias to the regression analysis. We employ a Control Function (CF) approach to estimate two correlated decisions in the following order: (1) the choice between semidwarf and conventional wheat and (2) the choice of nitrogen application rates given the choice of semidwarf wheat. The CF approach is especially useful in regressing multiple decisions that are affected by common factors. By using this technique, we estimate the effect of variety selection on nitrogen rates free of the impact of variables that move the two decisions simultaneously.

Our study area is Saskatchewan, Canada, which is a major wheat-producing region in North America. We found that by switching from conventional to semidwarf wheat, the per-acre nitrogen application rate is expected to increase by 5.9%. On the other hand, the direct N_2O emissions resulting from soil nitrogen inputs measured in per tonne of wheat production are not significantly different between conventional and semidwarf wheat. We later combine regression results of the CF with emission factors from the literature to calculate changes in fertilizer-induced direct N_2O emissions when Saskatchewan wheat farmers gradually switch from conventional wheat to semidwarf wheat. Our results suggest that when all wheat farms in Saskatchewan have finished adopting semidwarf varieties, the spring wheat acres in the province will produce 432 thousand tonnes CO_2eq of direct N_2O emission in one year through nitrogen application, the damage of which is valued at $21.62 million CAD.

This study reveals the consequences in GHG emissions following the adoption of popular semidwarf varieties. It contributes to the literature of both agricultural and environmental studies by connecting farm-level decisions to GHG emissions, examining the role of an individual farmer's choice in the grand issue of climate change. This study demonstrates the importance of improving the nitrogen-use efficiency in semidwarf varieties, supporting the idea of making the Green Revolution truly green (Wang et al. 2021). In addition, the results of this study may serve as a reference for designing policies that aim to tackle the GHG issue in the agricultural sector.

The rest of this study goes as follow: chapter 2 is a review of the existing literature. Chapter 3 provides detailed discussions of methodologies, data sources, and how specific variables are processed from the data. Chapter 4 contains data analysis and interpretations of regression results, followed by the estimation of fertilizer-induced direct N_2O emissions. Finally, chapter 5 concludes the findings of this study and provides policy recommendations.

Chapter 2

Literature Review

In this chapter, we present evidence and results collected from the literature. There are four sections that the literature review covers; a brief history of wheat breeding, the development of semidwarf wheat, past studies of variety adoptions, and the connection between crop farming and N_2O emissions.

2.1 The development of wheat breeding

The search for wheat varieties began with the expansion of wheat farming in more geographical locations and the spread of yield-sapping insects and diseases (Olmstead and Rhode 2002). Throughout the history of crop breeding, perhaps the most significant event is the Green Revolution (1960-1980). During this period, the productivity of field crops experienced a significant boost because of the adoption of genetically improved varieties. In this period, the boom in crop production can be attributed to the short stature, input efficiency, and disease resistance of these new varieties (Borlaug 1971). The adoption of modern varieties (averaged across all crops) increased rapidly during the Green Revolution, from 9 % in 1970 to 63 % by 1998 (Evenson and Gollin 2003). The yield potential of irrigated wheat worldwide increased by 1 % or $100\,\mathrm{kg\,ha^{-1}}$ every year during this period (Pingali 1999).

A channel through which wheat breeding takes place is international collaboration. One of the well-known international wheat breeding bodies is the International Maize and Wheat Improvement Centre (CIMMYT). CIMMYT is one of the 15 research centres of the Consultative Group on International Agricultural Research (CGIAR).

CIMMYT does not directly make improved varieties available to farmers. Rather, CIMMYT makes advanced lines available to the National Agricultural Research Systems (NARSs). The latter tests varieties and makes decisions regarding the release of new varieties (Byerlee and Traxler 1995). Released varieties are categorized into 3 classes: (1). Direct transfer of varieties from CIMMYT to countries after testing by NARSs. (2). Adaptive transfer of CIMMYT varieties for further variety breeding work by NARSs. (3). Varieties that involve no CIMMYT parents (Byerlee and Traxler 1995). As reported by Nalley et al. (2008), governments and agencies made up around 33% of CIMMYT's funding in 2002, including the U.S. (23%), the World Bank (23%), Switzerland (10%), the European Commission (9%), and the Rockefeller Foundation (8%). Other countries and foundations contributed to the remaining 27% from governments.

Many studies have demonstrated that the adoption of improved wheat varieties has a positive effect on productivity. For example, Byerlee and Moya (1993) suggest that the adoption of modern spring bread wheat varieties between 1977 and 1990 led to an additional 15.5 million tonnes of wheat production in 1990, which was worth roughly $3 billion USD. A more recent study by Lantican et al. (2005) pointed out that the hike in wheat yield in the developing world is attributed to the international wheat breeding research, which ranges from 14 to 41 million tonnes per year, which translates to $2 to $6.1 billion USD of monetary benefit per year (2002 dollars).

2.2 Semidwarf wheat

Semidwarf wheat varieties are those that carry semidwarf genes. These genes give plants short stems and thus make them more resistant to lodging, and they also provide plants with disease resistance and fertilization amenability (Biello 2009). The dwarfism of semidwarf wheat varieties is attributed to the reduced height (Rht) genes, which are originally carried by Asian varieties.

The Rht was introduced to western wheat industries through hybridization. In the U.S., the first source of Rht genes of wheat is the variety Norin 10, which is the result of cross breeding of Japanese and U.S. varieties between 1925 and 1932 (Dalrymple 1980). One of the early work groups that worked on crossing the Japanese semidwarf wheat with the U.S. varieties was headed by Dr Orville A. Vogel of the

U.S. Department of Agriculture (USDA). The first semidwarf variety in the U.S., Gaines, was developed by the Vogel group in the middle 1950s and officially released for production in 1961 (Dalrymple 1980). More semidwarf varieties were subsequently released in the next several decades. Another important name in the crossing of Asian dwarf varieties and western varieties is an Italian wheat breeder—Nazareno Strampelli. The first crossing work of Strampelli happened in 1913, in which he crossed the Japanese variety Akakomugi with Wilhelmina Tare × Rite to obtain new varieties Villa Gloria, Ardito, Mentana, and Damiano that are short, early mature, and high yielding (Lorenzetti 2000). Strampelli's varieties became the basis of wheat breeding in many other countries, including Argentina, Brazil, Australia, and Canada (Salvi et al. 2013). Strampelli's varieties are believed to be the foundation of Norman Borlaug's breeding work (Salvi et al. 2013). The latter significantly contributed to one of the most important events in the history of wheat breeding—the Green Revolution.

One of the distinguishing features of semidwarf wheat is its yield potential. In a multiple site-year comparison study, Allan (1986) found that certain semidwarf genes (Rht_1, Rht_3) generate 4% to 60% more kernels per spike compared to their control group (selected conventional varieties). The yield benefit of semidwarf varieties, however, does not always show up. For example, Laing and Fischer (1977) provide evidence showing that semidwarf varieties generally perform better than taller varieties when properly irrigated. In contrast, in dry areas such as North Dakota, which borders Saskatchewan, the yield potentials and responses to N fertilizer of semidwarf varieties are the same or worse than conventional varieties (Power and Alessi 1978).

Another favourable trait of semidwarf wheat is its responsiveness and tolerance to N fertilizer. The common perception is that semidwarf varieties have higher N uptake, and thus they produce higher yields than other varieties at a constant nitrogen rate. Evidence from the literature confirms this view: a study by Syme et al. (1976) found that while semidwarf varieties perform better than conventional varieties in terms of grain yield, they are also more responsive to nitrogen; another study by Blackman et al. (1978) also provides supporting evidence. Nevertheless, Loddo and Gooding (2012) demonstrates that although semidwarfing alleles increase the nitrogen-use efficiency and grain yield of wheat at a constant nitrogen application rate, this advantage wanes away when different alleles are compared at their economically optimal nitrogen rates. Semidwarf varieties indeed have lower nitrogen-use efficiency than taller varieties at their economically optimal nitrogen rates (Loddo and Gooding 2012).

In conclusion, semidwarf wheat has two major advantages compared to conventional varieties. First, it has better lodging and disease resistance. Second, semidwarf wheat requires more nitrogen input than conventional varieties to achieve optimal grain yields, which can lead farmers to increase their nitrogen use. In light of the benefits semidwarf wheat provide compared to conventional wheat, the province of Saskatchewan, as one of the leading wheat-producing regions, is gradually switching from conventional to semidwarf varieties. In recent years, the acreage of semidwarf wheat in Saskatchewan has reached to similar levels of conventional wheat, followed by changes in grain yields and nitrogen use (more details provided in Section 4.1). On the other hand, the yield of semidwarf wheat could be constrained by other elements such as soil moisture. Thus, resistance, nitrogen application rates, and their related factors are necessary to consider when modelling the adoption of semidwarf wheat. Moreover, when using yield as a regression variable, it may need to be accompanied by factors that indicate soil moisture levels.

2.3 Farmer's choice of varieties

A farmer's choice of wheat varieties is a relatively new subject of study, but the research on variety selection in general. The research on variety selection dates back to Griliches (1957)'s investigation of the adoption of hybrid corn in the U.S. Griliches suggested the adoption pattern is regional-specific; states where the profitability of hybrid corn is higher appeared to have faster-growing adoption rates.

One of the first studies that acknowledge farmers' roles in wheat variety selection is Traxler and Byerlee (1993). In comparing semidwarf and conventional wheat varieties, Traxler and Byerlee assumed wheat to have two desirable outputs—grain and straw. The former is a directly marketable output and the latter is a source of fodder. Farmers choose wheat varieties that fit their demands for grain and fodder. They also assumed the technical evolution in varietal development takes two forms. The first one occurs when a new variety yields a similar quantity of dry matter compared to the conventional variety, but has a different harvest index (e.g., greater quantity yield compared to straw). The second form occurs when a new variety produces more grain as well as more straw than the conventional variety. By constructing a profit-maximizing framework, Traxler and Byerlee (1993) suggested that the selection of varieties is determined by the price ratio of outputs (price of grain/price of straw). A great contribution of this work is that it acknowledges the values of both conventional and improved varieties, and having a dominating variety in terms of adoption rate is not necessary to achieve profit maximization. However, its exclusion of farm-specific variables other than nitrogen application rate may bias the results.

Heisey et al. (1997) employed a utility-maximizing framework to model the adoption of rust-resistant wheat varieties in Pakistan. An advantage of this study is that it focuses on producers' welfare instead of pure profit, which allows for the interpretation of non-monetary factors that may affect choices. In this framework, each farmer chooses varieties to maximize their utility conditional on the choices made by others. This work provides two pieces of important information. First, farmers grow high-yielding varieties regardless of how rust-resistant they are. Second, farmers grow high-yielding varieties whether or not they have the same basis of genetic resistance as those grown by other farmers (Heisey et al. 1997). Although the main target of this study is to address the issue of on-farm genetic diversity, the results support the idea that yield is the dominant factor in farmers' variety selection. For this reason, farmers may stick to conventional varieties that are viewed as inefficient by governmental agencies and scientists, despite the availability of more advanced alternatives.

More recent studies look at farmers' preferences for disease and climate resistance of wheat varieties. The desire for resistance traits, however, varies by geographical location. In dryer regions, for example, farmers would prefer drought and heat-resistant varieties. In a choice experiment by Kassie et al. (2017), the drought tolerance trait of maize determines Zimbabwean farmers' adoption to a magnitude as least as great as yield. Another study in Ethiopia found that farmers are willing to pay 10 times the value they are willing to pay for a 100kg/ha yield increase for yellow rust resistance and frost resistance (Teferi et al. 2020). Given the severity of risks faced by farmers in subject regions, the preference for stability over profitability is well-grounded. Subsequent studies also confirmed the significance of disease and climate resistance traits in farmers' preference (Sánchez et al. 2017; Acheampong et al. 2018; Coromaldi et al. 2015).

Farm and farmer characteristics are another source of preference heterogeneity. For instance, farm size is an essential factor that affects adoption decisions. Larger farms are less risk-averse as they are more likely to have other sources of income (e.g., livestock), making them ready to adopt crop varieties that are more productive but less resilient and less stable in terms of yield. (Asrat et al. 2010). The diversification in income sources helps offset any profit losses occurred in some on-farm productions. Besides, the access to off-farm income is also associated with choosing modern varieties (Chebil et al. 2009). The level of education, to some degree, increases the probability of adopting new technology by providing farmers with knowledge of operating the new technology (Hiebert 1974; Begum et al. 2018; Asfaw and Admassie 2004). Gender and age also appear to have a role, though disagreements exist over the direction of the age effect (Coromaldi et al. 2015; Asfaw and Admassie 2004); Benin et al. 2004).

Hence, while yield may be the top determinant in variety selection, other factors such as agronomic practices, farm characteristics, and weather also appear to be important. For this reason, one should consider incorporating these variables when studying the adoption of semidwarf wheat.

2.4 Nitrous oxide emissions from crop farming

Connecting wheat varieties and environmental quality is a relatively new topic. Previous studies support the idea that variety selection can affect N_2O emissions. This section presents evidence from the literature which can facilitate future investigations on this topic.

In a field experiment designed to study the dynamics of N_2O emission from rice and wheat fields, Gogoi and Baruah (2012) found that N_2O emissions took a wide-ranging interval for the 4 wheat and 3 rice varieties selected. Their results suggest that wheat varieties that generate less emission are not necessarily compromised in yield. They also point out that emission is correlated with the soil organic carbon, soil temperature, and the dry weight of plants.

Weather also affects nitrogen emissions in crop farming. Precipitation and temperature are the two most recognized factors. Soil nitrate concentrations are generally lower in years with ample precipitation, and nitrogen concentrated and leached both increase with temperature (Jabloun et al. 2015). Another study by Liang et al. (2011) observed the same pattern, that rainfall and temperature jointly determine the variation in soil nitrate concentration. Woli and Hoogenboom (2018) further connected weather and nitrate leaching with soil types, indicating that lighter soil types generally experience more nitrate leaching with an increase in irrigation. Therefore, weather conditions greatly affect soil nitrogen emission, and failing to control for them may result in miscalculation of the effect of adopting semidwarf wheat on N_2O emissions.

Additionally, a common belief is that crop rotations affect N residues in the soil, and thus affecting nitrous flux in the next cropping season. However, recent studies have not found sufficient evidence supporting this idea. Lemke et al. (2018) suggests that though the amount of residual N in the soil does vary with preceding crops, no significant relationship was found between residue N and cumulative N_2O emissions. Jeuffroy et al. (2013), who undertook a similar study in a different growing environment, also reached a similar conclusion. However, even though residual N does not have a strong effect on cumulative N_2O emissions, we cannot rule out the possibility that farmers may adjust nitrogen application rates based on the previous crop.

To summarize, agronomic practices, geographical characteristics, and weather conditions jointly affect nitrogen emissions. In contrast, no direct evidence was found regarding whether semidwarf wheat emits more N_2O relative to conventional varieties when the same amount of nitrogen is applied. Nevertheless, as previous studies suggest that semidwarf wheat varieties allow farmers to apply more nitrogen, the quantity of N_2O emission could increase because of changes in nitrogen application rates.

Chapter 3

Methodology

This chapter goes over the data and methodology used to predict changes in N_2O emissions when adopting semidwarf wheat. A description of the data is provided first before introducing the method of estimation. The method contains two parts: (1) estimating the impact of adopting semidwarf wheat instead of conventional wheat on nitrogen use and (2) predicting the expected changes in N_2O emissions.

3.1 Data

Saskatchewan is a prairie province in western Canada and a major wheat-producing region in North America, which makes it a candidate study region. In the last decade, 10-14 million acres of wheat were seeded in Saskatchewan in each year (Statistics Canada 2021). This number was about half of the total seeded area of wheat in Canada. The extent of wheat farming in Saskatchewan is substantial; in 2016, a total of $17,650$ farms have reported producing wheat (Statistics Canada 2017). The extent of wheat production in Saskatchewan can potentially provide us with adequate data to work with.

The major source of data for this study is the *Saskatchewan Crop Insurance Corporation* (SCIC). The SCIC data contains insurance information of registered Saskatchewan farmers and self-reported farm statistics. The uniqueness of the data is that it is a field-level panel data with information specific to each field, such as coordinates, crop and variety selected, and nitrogen applied per acre. According to the varieties selected by farmers in each year in each field, we differentiate fields by whether they are seeded with semidwarf or conventional wheat. More importantly, the data suggests that Saskatchewan wheat farmers are in the middle of transitioning from conventional to semidwarf wheat. The current adoption status of semidwarf and conventional wheat varieties in Saskatchewan makes comparisons between the two types of wheat readily accessible.

Due to the disturbance in the wheat market because of the global pandemic starting in 2020, we do not use data generated after 2019 to exclude this external shock from our estimates. Moreover, only farmers who participate in the *Management Plus* program report nitrogen rates to the SCIC. Although records of nitrogen use in our data start in early 2000, they remain missing for a large number of fields until 2010. Thus, we exclude data before 2010. As our model includes a crop rotation variable, 2010 becomes the year that has no information regarding previous crops. Thus, our analysis focuses on 2011 to

2019. As suggested by our data, about 63% of fields in Saskatchewan (all crops) have reported nitrogen application rates between 2011 and 2019.

Expected yields and information regarding disease resistance are found in the *Saskatchewan Crop Guide* published annually by the Saskatchewan Seed Growers Association (2022). Disease resistance measures are included as a five-level categorical variable.

The expected yield of each variety came from field tests conducted in four testing areas in Saskatchewan (see area numbers in Figure 3.1), the results of which are recorded in the Saskatchewan Crop Guide. Area 1 is the brown soil zone and area 2 is the dark brown soil zone. Areas 3 and 4 are more complex in terms of soil types. In this study, we follow the *Saskatchewan Crop Planning Guide* published by the Ministry of Agriculture (2022) to categorize soil zones as black, brown, and dark brown. Soil zone locations according to each agency are provided in Figures 3.1 and 3.2. The original yield indices were measured as ratios to the yield of a "check" variety. Specifically, the check variety has a yield index of 100, and a variety that has 10% more expected yield than the check variety has an index of 110. Because the check variety used in the Crop Guide changes periodically, all variables that are subject to a check variety are converted to as if they have the same check variety. The check variety used in this study is *Carberry*. Unfortunately, not all varieties that appear in the SCIC data show up in the Crop Guide. We keep only varieties that appear in both datasets. A total of 56 spring wheat varieties are included in the data used for the regression model.

Daily precipitation and average temperature are recorded by weather stations, the data from which can be found in the Government of Canada (2021a). Weather data used in this study is created by (1) mapping the distance of each field to all weather stations in Saskatchewan, and (2) extract historical precipitation and temperature records from the nearest weather station and use them as the weather data of that field. The two weather variables in the regression model, total precipitation and growing season mean temperature in the previous year, are calculated by summing the daily records to annual levels.

The final sample used in the analysis contains $54,243$ distinct fields in Saskatchewan, making $95,556$ observations between 2011 and 2019.

3.1.1 Defining semidwarf wheat

The most easily identifiable characteristic differentiating semidwarf and conventional wheat, especially when genomics information is not available, is height. A common rule-of-thumb is to use the height of the variety Carberry as the cut-off height—any wheat varieties shorter than Carberry are considered semidwarf. The Carberry cut-off is an accepted industrial standard for distinguishing semidwarf and conventional wheat varieties, and the variety Carberry has been used as a comparison baseline when studying properties of other wheat varieties (e.g., Wu et al. 2019; Tabil et al. nd). However, as new varieties

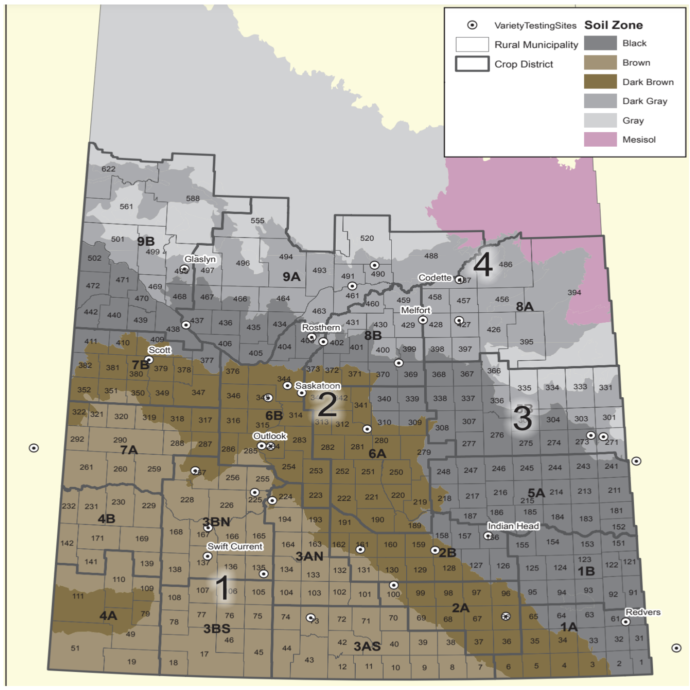

Figure 3.1: Source: SaskSeed Guide 2022

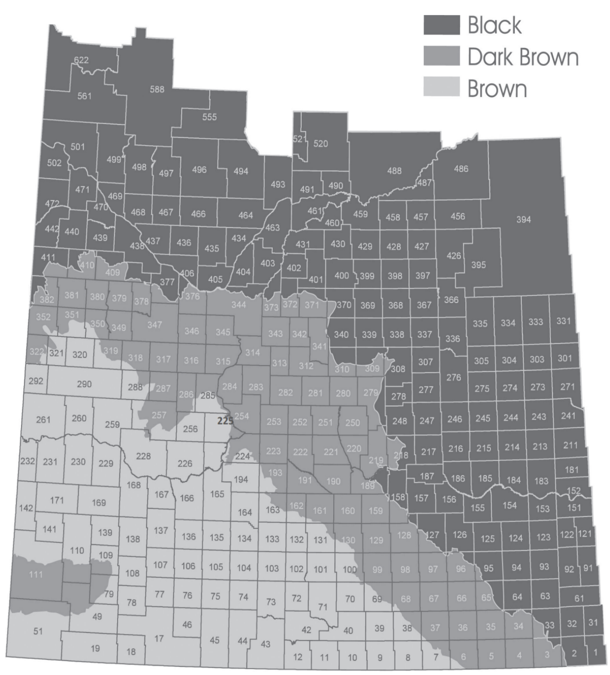

Figure 3.2: Source: Saskatchewan Crop Planning Guide 2022

emerge, this rule-of-thumb is no longer accurate as some newer semidwarf varieties can be taller than Carberry. Despite that height may not be the most effective standard to separate the two wheat families, it is the best to use with the data available. To ensure that the results are robust to the Carberry cut-off, we also re-estimate the model at nearby cut-offs.

According to our data, the average height of Carberry is 83cm. Under this cut-off, there are $74,412$ fields seeded with conventional wheat and $21,144$ seeded with semidwarf wheat in Saskatchewan between 2011 and 2019. The robustness tests will use 86cm and 88cm as alternative cut-offs. More discussion on the differences in adoption status and other statistics between the two wheat families are provided in chapter 4.

3.2 Empirical Framework

In this section, we describe the model structure that this study uses to estimate the effect of adopting semidwarf wheat on nitrogen application rates. After reviewing the existing literature, we expect a couple of factors to be grounds for farmers' choices of varieties and the amount of nitrogen to apply.

3.2.1 Decisions for variety selection and nitrogen use

To begin with, the potential yield will be one of the most influential factors in the choice of varieties. Yield is also expected to be correlated with the amount of nitrogen farmers apply. However, the effect of nitrogen may go either way; varieties with higher yields do not necessarily have higher nitrogen-use efficiency (Loddo and Gooding 2012). Therefore, the correlation between variety selection and expected nitrogen use may not be positive in some cases. Given that input costs and output prices also determine the operation of a farm, we include yearly per-unit prices of nitrogen fertilizer and wheat grain in Saskatchewan.

Another factor to include is soil. We learn from Woli and Hoogenboom (2018) that soil type can affect nitrate leaching. Given that semidwarf wheat requires higher nitrogen rates to achieve optimal production levels, and that soil nutrition is typically different across soil types, we expect soil factors to affect farmers' decisions regarding the adoption of semidwarf wheat and nitrogen use. Thus, a soil zone variable is included to identify variations in soil characteristics in Saskatchewan.

Moreover, precipitation has an important role to play in the yield of wheat (Laing and Fischer 1977; Power and Alessi 1978) and thus may also affect farmers' choices. In this study, we use precipitation in the previous year to capture farmers' expectations regarding the soil moisture levels of their fields in the current year. Because temperature can also determine soil moisture (e.g., through evaporation), we use the growing season average temperature in the previous year to capture expectations regarding the temperature in the current growing season.

Additionally, although whether crop rotation can affect N_2O emissions through residual N is unclear according to Lemke et al. (2018) and Jeuffroy et al. (2013), farmers may adjust nitrogen rates based on the amount of residual N leftover from the previous crop. To capture such effects on farmers' behaviors, our model exhibits a variable that specifies the type of the previous crop.

As Asrat et al. (2010) suggested, farm size also affects the adoption status of some crop varieties because it is associated with the diversity in income sources and thus the ability to endure yield losses. We use the total insurance liability of each farmer in each year to reflect the size of their farm.

Lastly, the resistance to disease and natural disasters is an important reason farmers prefer a variety. For this reason, we include resistance ratings of each variety for some diseases that are commonly seen in North America.

After identifying the factors that our model needs to incorporate, we define a farmer's choices of varieties and nitrogen use with a system of two equations:

$$
\begin{aligned}
Semidwarf_{ijkt} = \beta_0 + &\beta_1 SoilZone_j + \beta_2 TotalPrecipLag_{j,t-1} + \\
&\beta_3 GSMeanTempLag_{j,t-1} + \beta_4 PreviousCrop_{j,t-1} + \\
&\beta_5 ln(WheatPrice)_t + \beta_6 ln(NPrice)_t + \\
&\beta_7 ln(ExpectedYield)_k + \beta_8 TotalLiability_{i,t} + \\
&\beta_9 StemRustResistance_k + \beta_{10} LeafRustResistance_k + \\
&\beta_{11} Year_t + \epsilon_{ijkt}
\end{aligned}
\tag{3.1}
$$

$$
\begin{aligned}
lnNitrogen_{ijkt} = \delta_0 + &\delta_1 Semidwarf_{ijkt} + \delta_2 SoilZone_j + \delta_3 TotalPrecipLag_{j,t-1} + \\
&\delta_4 GSMeanTempLag_{j,t-1} + \delta_5 PreviousCrop_{j,t-1} + \\
&\delta_6 ln(WheatPrice)_t + \delta_7 ln(Nprice)_t + \delta_8 ln(ExpectedYield)_k + \\
&\delta_9 TotalLiability_{it} + \delta_{10} Year_t + \upsilon_{ijkt}.
\end{aligned}
\tag{3.2}
$$

Index i stands for each farmer. j denotes each field that belongs to the same farmer. k refers to each wheat variety. t is the index for year. Coefficients of variables are denoted β's and δ's in Equations 3.1 and 3.2, respectively. The error terms are ϵ and υ.

$Semidwarf$ is a binary indicator in which 1 stands for that the variety on a specific field in a given year is semidwarf, 0 otherwise. $ln(Nitrogen)$ is the natural logarithm of the nitrogen application rate (lbs per acre) of a specific field in a given year. $ln(ExpectedYield)$ is the natural logarithm of the yield index of a variety. Note that a variety can have different yield indices in different soil zones. The reference variety Carberry has a yield index of 100 in all soil zones before log transformation. $SoilZone$ is a three-level categorical variable for soil zones in Saskatchewan. The soil zones are “black”, “dark brown”, and “brown”. $TotalPrecipLag$ is the annual cumulative precipitation (mm) in each field, which enters the model with a lag of 1 to mirror farmers’ expectations of soil moisture in the current year. $GSMeanTempLag$ is the average growing season temperature in each field, which is also lagged by 1 to serve as the variable representing farmers’ expectations regarding the growing season temperature in the current year. $PreviousCrop$ represents the type of crop seeded in each field in the previous year. Crops are broadly classified as cereal crops, pulse crops, and oilseeds. The crop seeded in the previous year may determine the amount of residues in the soil, affecting the amount of fertilizer needed for the next crop. $ln(WheatPrice)$ and $ln(NPrice)$ are the log-transformed prices of wheat and nitrogen fertilizer in each year. $TotalLiability$ is the annual total liability of a farmer’s wheat acres in a given year.

$StemRustResistance$ and $LeafRustResistance$ are referred to as the “resistance variables” in this study. They indicate the levels of resistance in a variety to stem rust and leaf rust, respectively. A more detailed description of the resistance rating scales can be found in section 3.1.

Finally, the $Year$ variable controls for other factors that vary from year to year.

One issue this system of equations has is simultaneity. A farmer's decision of nitrogen use is likely to vary with the chosen variety. That is, the semidwarf status shows up as both the output variable in Equation 3.1 and an explanatory variable in Equation 3.2. If we regress the two equations using a simple OLS, the two regression models will move simultaneously, introducing bias to the parameter estimates. To address this issue, we use a Control Function (CF) approach.

3.2.2 Control Function treatment for simultaneity

A CF model solves the issue of simultaneity with a two-stage approach. With appropriate instruments, the first stage isolates part of the variation in the choice of nitrogen rate that is correlated with the choice of wheat variety, and then uses it as an independent variable in the second stage that regresses the choice of nitrogen rate. In doing so, the endogenous variation is picked out from the second stage, and the parameter estimates are expected to be free of simultaneity bias.

For simplicity, we assume $ln(Nitrogen)$ and $Semidwarf$ are scalars and write Equation 3.2 as

$$ln(Nitrogen) = \delta_1 Semidwarf + \mathbf{z_1}\boldsymbol{\delta}^* + \upsilon, \tag{3.3}$$

in which $\mathbf{z_1}$ is a vector containing variables in Equation 3.2 other than $Semidwarf$, and $\boldsymbol{\delta}^* = \delta_2, \delta_3, \cdots, \delta 10$. Vector $\mathbf{z_1}$ is a subvector of $\mathbf{z} = (\mathbf{z_1}, \mathbf{z}_2)$. $\mathbf{z_2}$ contains $StemRustResistance$ and $LeafRustResistance$, which are exogenous variables omitted in Equation 3.3. A key property of vector $\mathbf{z}$ is that

$$E(\upsilon|\mathbf{z}) = 0. \tag{3.4}$$

Next, suppose that the endogenous variable $Semidwarf$ is partially correlated with $\mathbf{z}$. We simplify and re-write Equation 3.1 as

$$\begin{aligned} & Semidwarf = 1[\mathbf{z}_1\boldsymbol{\beta}_1 + \mathbf{z}_2\boldsymbol{\beta}_2 + \epsilon > 0] \\ & E(\mathbf{z}_1, \epsilon) = 0 \\ & E(\mathbf{z}_2, \epsilon) = 0, \end{aligned} \tag{3.5}$$

where $1[\cdot]$ is the binary indicator function, and ϵ is the error term of equation 3.5. Vector $\boldsymbol{\beta}_1 = \beta_1, \beta_2, \cdots, \beta_8, \beta_{11}$ and vector $\boldsymbol{\beta}_2 = \beta_9, \beta_{10}$ are the same coefficients as in Equation 3.1. Notice that the rank condition of a simultaneous equation model is satisfied if and only if $\boldsymbol{\alpha}_2 \neq \mathbf{0}$ (Wooldridge 2015).

From Equation 3.3 and Equation 3.5, we can tell the two errors, ϵ and υ, are partially correlated. Accordingly, we can express their relationship as

$$\begin{aligned} & \upsilon = \theta\epsilon + \eta \\ & E(\epsilon\eta) = 0. \end{aligned} \tag{3.6}$$

By inserting Equation 3.6 into Equation 3.3, we get

$$ln(Nitrogen) = \delta_1 Semidwarf + \mathbf{z_1}\boldsymbol{\delta}^* + \theta\epsilon + \eta. \tag{3.7}$$

The variable ϵ can be interpreted as the endogenous portion of $Semidwarf$. By including it, we get a new error term, η, such that

$$E[\eta|Semidwarf, \mathbf{z}_1, \epsilon] = 0. \tag{3.8}$$

In a CF with a binary endogenous independent variable, a probit model is often used. To derive a probit model, we need to assume that ϵ has a normal distribution with a mean of 0 and standard deviation of 1, and υ is a linear function of ϵ (Wooldridge 2015). When these two assumptions are satisfied, a probit model is given as

$$P(Semidwarf = 1|\mathbf{z}) = \boldsymbol{\Phi}(\mathbf{z}\boldsymbol{\beta}), \tag{3.9}$$

where $\boldsymbol{\Phi}(\cdot)$ is the cumulative distribution function of a standard normal distribution, and $\boldsymbol{\beta} = (\boldsymbol{\beta}_1, \boldsymbol{\beta}_2)$.

By following the steps in Wooldridge (2010, 2015), we can write the conditional expected value of $ln(Nitrogen)$ as

$$\begin{aligned} &E(ln(Nitrogen)|\mathbf{z}, Semidwarf) \\ =&\mathbf{z_1}\boldsymbol{\delta}^* + \delta_1 Semidwarf + \pi[Semidwarf\lambda(\mathbf{z}\boldsymbol{\beta}) - (1 - Semidwarf)\lambda(-\mathbf{z}\boldsymbol{\beta})], \end{aligned} \tag{3.10}$$

where $\lambda(\cdot)$ is the inverse Mill's ratio. The term $Semidwarf\lambda(\mathbf{z}\boldsymbol{\beta})-(1-Semidwarf)\lambda(-\mathbf{z}\boldsymbol{\beta})$ is referred to as the generalized residual which has a zero mean conditional on $\mathbf{z}$, and π is its associated coefficient in Equation 3.10.

The fact that the resistance variables are omitted in Equation 3.3 creates an ideal setup for implementing the CF treatment. The first reason is that semidwarf wheat varieties are expected to have different levels of disease resistance compared to conventional wheat (Biello 2009). Another reason is that they are unlikely to affect the amount of nitrogen a farmer uses. To address these two diseases, farmers would require some other agricultural chemicals than nitrogen fertilizer.

To implement a CF model in this study, we follow a two-stage procedure. The first stage is to regress Equation 3.9, which will allow us to calculate the generalized residuals, denoted $\hat{r}$. Next, regress $ln(Nitrogen)$ on $Semidwarf$, $\mathbf{z}$, and $\hat{r}$ to consistently estimate $\boldsymbol{\delta}^*$, δ_1, and π. The estimated value of δ_1 is the expected effect of adopting semidwarf wheat instead of conventional wheat on the nitrogen application rate. Notice that one should account for the generated regressors from the first-stage estimation. We follow Wooldridge (2014) to bootstrap the two estimation stages to account for the sample variation in estimated regressors.

We will model and perform any related analysis in $R(4.1.1)$.

3.3 Measuring Direct N_2O Emissions

After estimating the marginal effect of adopting semidwarf wheat on nitrogen application rate, the subsequent impact on direct N_2O can be obtained by combining the estimated marginal effect with emission factors (EFs) and emission functions that are readily available in the literature. Nevertheless, the literature does not offer sufficient evidence to suggest that semidwarf and conventional wheat varieties differ in nitrogen-use efficiencies (e.g., Loddo and Gooding 2012). For this reason, in the event that our regression results suggest farmers do apply more nitrogen to semidwarf wheat relative to conventional wheat, the only type of emission that is guaranteed to differ between semidwarf and conventional varieties is the direct N_2O emission resulted from soil nitrogen inputs. Therefore, this study solely focuses on direct soil N_2O emissions induced by nitrogen applications, or in other words, the fertilizer-induced direct N_2O emissions. Emissions produced during the manufacturing and transportation processes of nitrogen fertilizer are not within the scope of this study.

Hence, it should be noted that any estimations regarding emissions in this study do not cover the full emission of nitrogen application. Indeed, direct N_2O from managed soil comes from multiple sources. While nitrogen fertilizer is the most important source of direct N_2O emissions, other sources include urine and dung from grazing animals, crop residuals, and mineralization of soil organic matters (Canadian Roundtable on Sustainable Crops 2017). Tillage practices, summer fallow, and irrigation can also influence soil N_2O emissions (Environment and Climate Change Canada 2021c). Nitrogen fertilizer is further categorized into synthetic and organic fertilizer. Because the type of fertilizer is not reported in the data, we assume all reported fertilizer application rates in the SCIC data refer to synthetic fertilizer. As only fertilizer-induced direct N_2O emissions are considered in this study, the estimates will be smaller than the total direct N_2O emission from agricultural soils reported in other studies (e.g., Environment and Climate Change Canada 2021b, Canadian Roundtable on Sustainable Crops 2017).

We estimate emissions in Saskatchewan with different regional specifications. The province of Saskatchewan can be divided into different soil zones based on soil characteristics. There are three soil zones in Saskatchewan according to the Ministry of Agriculture (2022): black, brown, and dark brown. Based on the results of Rochette et al. (2018), the brown and dark brown soil zones have similar soil direct emissions in response to nitrogen inputs, and thus we group them into one category. Therefore, we estimate fertilizer-induced direct N_2O emissions with three regional specifications: (1) the entirety of Saskatchewan, (2) the black soil zone, and (3) brown plus dark brown soil zones. EFs for these three regions are provided by Rochette et al. (2018). The interpretation of EFs is fairly straightforward; for every unit of nitrogen input, an EF is the quantity of N_2O-N emitted. According to Rochette et al. (2018), the mean EF for both synthetic and organic N inputs is $0.0019\text{kg}\,N_2O{-}N\,\text{kg}^{-1}\,N$ for Prairie regions, and it will be used as the EF for the entirety of Saskatchewan. When soil zones are considered, the EF for synthetic nitrogen is 0.0033kg $\mathrm{N_2O{-}N\,kg^{-1}\,N}$ for the black zone and 0.0016kg $\mathrm{N_2O{-}N\,kg^{-1}\,N}$ for brown plus dark brown soil zones. These estimates are lower than the default values provided in IPCC (2019), which are 0.01kg $\mathrm{N_2O{-}N\,kg^{-1}\,N}$ globally and 0.05kg $\mathrm{N_2O{-}N\,kg^{-1}\,N}$ in dry regions.

Under the United Nations Framework Convention on Climate Change (UNFCC), each participating government submits a National Inventory Report (NIR) to announce its current state with respect to GHG emissions. A NIR reports multiple types of GHGs produced within a country, usually by economic sectors. The quantities of emissions are calculated following international guides (usually the IPCC) and the results of previous research. We use the formula provided in the NIR submitted by the ECCC (Environment and Climate Change Canada)(2021c) to calculate direct N_2O emissions from soil nitrogen inputs:

$$\mathrm{N_2O}_{SFN} = \sum_i (\mathrm{N}_{FERT,i} * EF_{BASE,i} * RF_{TEXTURE,i}) * \frac{48}{22} * 298, \quad (3.11)$$

where $\mathrm{N_2O}_{SFN}$ is the per-year direct N_2O emission generated by soil nitrogen inputs measured in kg CO_2eq. $\mathrm{N}_{FERT,i}$ is the quantity of synthetic nitrogen fertilizer used in area i. In the original report (ECCC, 2021c), i refers to ecodistricts, which groups land based on environmental and geological characteristics. Here, i denotes soil zones instead. $EF_{BASE,i}$ is the emission factor for area i. $RF_{TEXTURE,i}$ is the indicator for soil texture in area i. For Prairie regions, $RF_{TEXTURE,i} =$

1 is used given the low soil water content leads to low N_2O emission regardless of the soil texture (Rochette et al. 2008). The ratio 48/22 is a multiplier that converts kg N_2O-N to kg N_2O. We follow IPCC Working Group I's fourth report (2007) and use a global warming potential of 298 in a 100-year lifetime for N_2O to convert N_2O to CO_2eq.

Note that our sample contains only a proportion of spring wheat grown in Saskatchewan, and therefore our estimates of emissions are not at the provincial level. For this reason, we mainly report the emission per tonne of grain production in each year.

The values of the environmental damage are calculated by multiplying the quantity of direct N_2O emission by a Social Cost of Carbon (SCC). This study employs the most up-to-date SCC used by the ECCC (2020), which is \$50 CAD tonne^{-1} CO_2eq in 2019 dollars. SCCs used by the ECCC (2020) are estimated based on research and analysis conducted by the U.S. Interagency Working Group on SCC, and they have been adopted by the Government of Canada since 2011 (ECCC 2016).

Chapter 4

Results and Discussion

This chapter contains the analysis of data and regression results. We compare semidwarf wheat and conventional wheat in Saskatchewan on their adoption status, yields, and nitrogen inputs. Next, we analyze the regression results by interpreting factors that affect variety selection and nitrogen input, as well as how choosing semidwarf wheat subsequently impacts nitrogen application rates compared to conventional wheat. Lastly, we predict fertilizer-induce direct N_2O emissions using our regression results.

4.1 Comparison between semidwarf and conventional wheat

The descriptive statistics in Table 4.1 demonstrate that semidwarf wheat shows some noticeable differences from conventional varieties.

In all three soil zones in Saskatchewan, the acreage devoted to conventional wheat per year is at least 3 times that of semidwarf wheat. Moreover, semidwarf wheat receives about 10 lbs more per acre of nitrogen relative to conventional wheat. In Saskatchewan, the average production rate (tonnes per acre) of semidwarf wheat is about 13% higher than conventional wheat across all soil zones.

When we plot the acreages in each year (Figure 4.1), we see that the acreage of conventional wheat is decreasing over time in all three soil zones. However, the acreage of semidwarf wheat is increasing and matching the level of conventional wheat between 2018 and 2019. This pattern indicates that Saskatchewan is undergoing a transitioning period from conventional to semidwarf wheat varieties. The variation in adoption status across soil zones appears to be clear; darker soil zones are seeded with more semidwarf wheat. Such regional variation confirms the finding of Shiferaw et al. (2014) that spatial and ecological effects exist in the adoption of improved wheat varieties.

Table 4.1: Comparison between semidwarf and conventional wheat.

Soil zone	Black		Brown		Dark brown	
Variety type	Con.	Sem.	Con.	Sem.	Con.	Sem.
Annual* mean acreage (1000ac)	595.22	191.80	92.47	24.05	377.11	92.79
Annual mean nitrogen rate (lbs/ac)	80.44	88.42	60.59	72.92	74.28	81.33
Annual mean production rate (tonnes/ac)	1.34	1.51	1.00	1.14	1.21	1.36

*Data used to calculate annual means covers 2011 to 2019

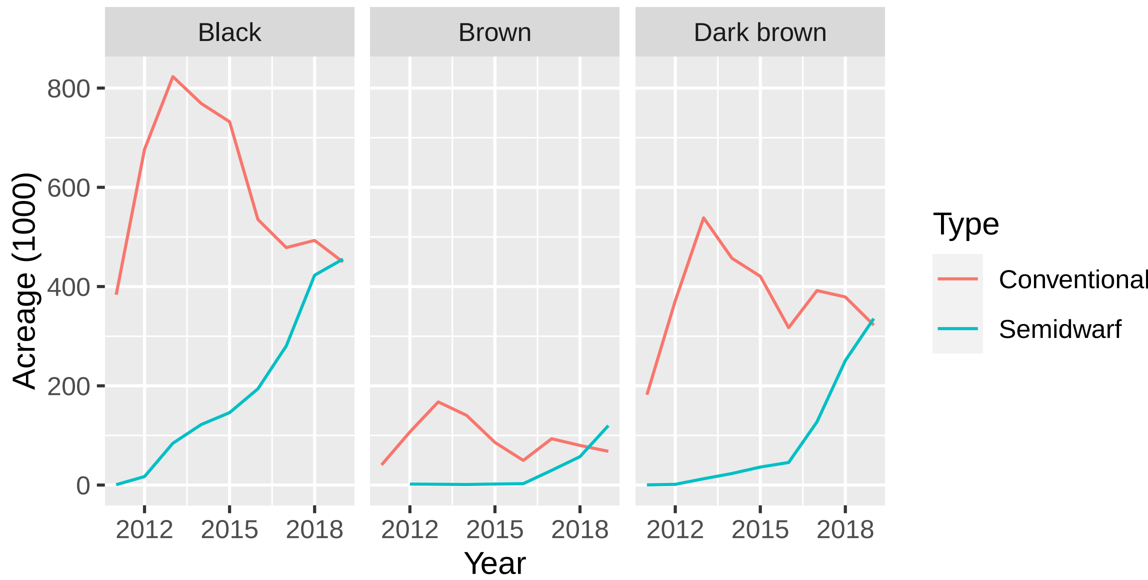

Figure 4.1: Total seeded acreage of each type of wheat in Saskatchewan between 2011 and 2019

The trends in nitrogen application rates also show interesting patterns (displayed in Figure 4.2). While semidwarf wheat has a higher nitrogen application rate in most circumstances (with the exception of the dark brown soil zone in selected years), the nitrogen application rates for both variety types are increasing over the years. Changes in the cost of nitrogen (Figure 4.3) may partially explain this upward trend; the more affordable nitrogen is, the more likely farmers increase their application rates.

Although we know that the per-year production rates of semidwarf wheat are higher than conventional wheat (shown in Table 4.1), the two types of wheat actually have very similar trends in production rates when we plot them by years (shown in Figure 4.4). Unlike the patterns in acreage and nitrogen application rates, in which we can see a clear difference between the two variety types, the yield performance of semidwarf wheat is not always superior. However, semidwarf wheat does have higher production rates in most years. Another important finding is that there are likely to exist some other factors affecting the production of both types of wheat, given how close the two trends follow each other in all three soil zones.

In terms of yields, it appears that the yield benefit of adopting semidwarf wheat is the most prominent in the brown soil zone (see Figure 4.4). This could be a result of that the gap in nitrogen rates of semidwarf and conventional wheat is much bigger in the brown soil zone (Figure 4.2).

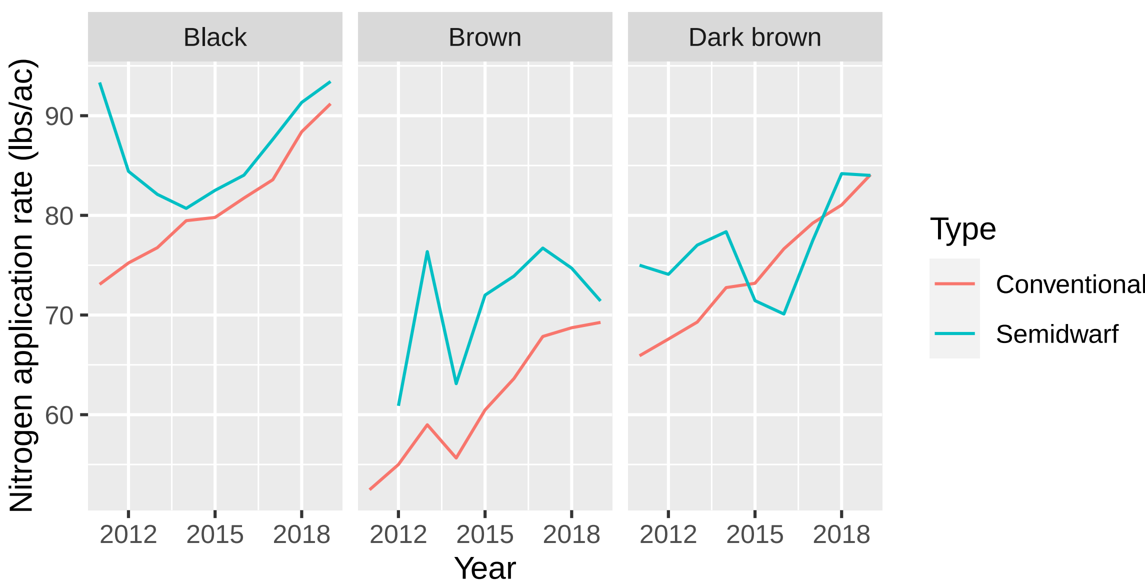

Figure 4.2: Average nitrogen application rates of spring wheat in Saskatchewan between 2011 and 2019

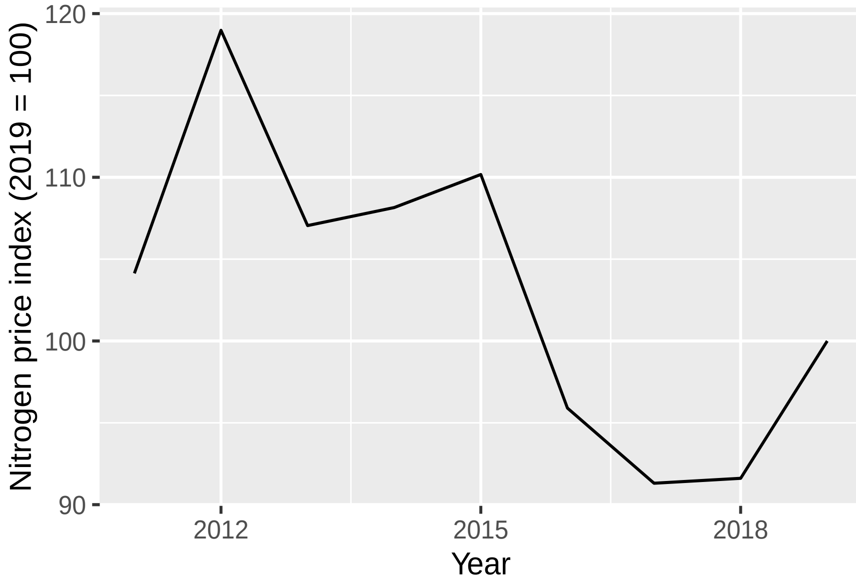

Figure 4.3: Nitrogen input price index in Saskatchewan between 2011 and 2019

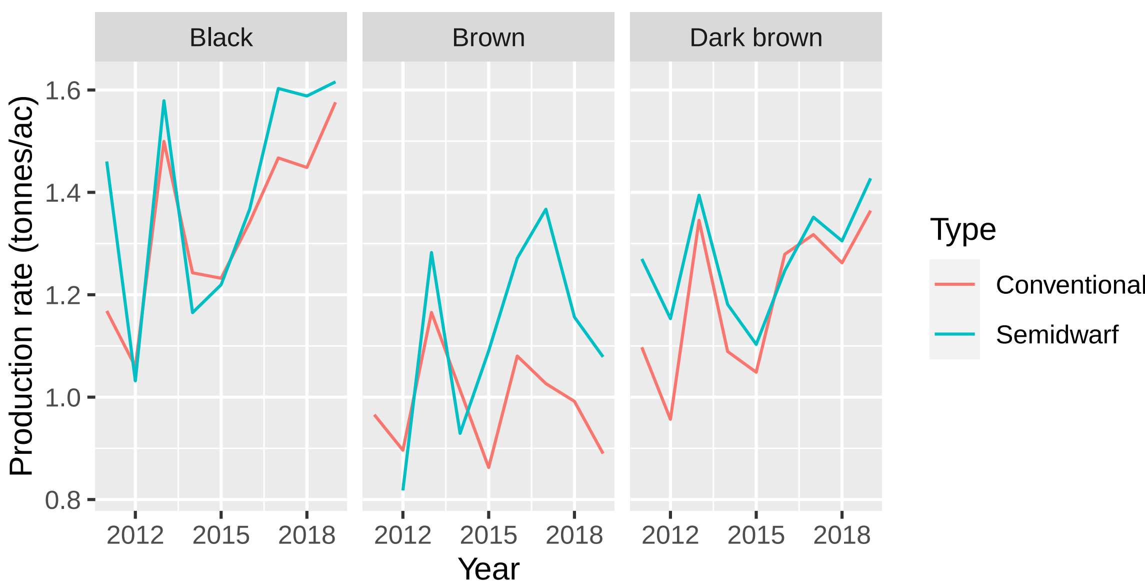

Figure 4.4: Average annual production rates of spring wheat in Saskatchewan between 2011 and 2019

4.2 Regression Results

Table 4.2 contains results from the CF regression model. Because of the complexity in interpreting coefficient estimates of a probit model, these results have been converted to marginal effects. All estimates should be interpreted under the assumption that other factors stay constant.

On average, farmers apply 5.9% more nitrogen per acre to semidwarf wheat compared to conventional wheat. When compared with other effects (e.g., soil zone, previous crop), choosing semidwarf varieties is not the most influential factor that makes farmers apply more nitrogen.

In the soil zone effects, the black soil zone is treated as the base level. On average, farmers in the brown soil zone are 13% less likely to choose semidwarf wheat relative to those who are in the black soil zone. While the yields of semidwarf wheat seem to be higher than conventional wheat most frequently in the brown soil zone (Figure 4.4), the overall production rates of both types of wheat are lower in the brown soil zone relative to the other two soil zones, which could explain why farmers in the brown soil zone are less likely to choose semidwarf varieties. In the dark brown soil zone, farmers are 10% less likely to choose semidwarf wheat compared to in the black soil zone.

Overall, farmers apply less nitrogen fertilizer to fields that are not in the black soil zone. The quantities of nitrogen fertilizer applied per acre in brown and dark brown soil zones are 23% and 6.6% less than that in the black soil zone, respectively. This finding is likely to be correlated with the difference in the popularity of semidwarf wheat across soil zones; as farmers in brown and dark brown soil zones have smaller probabilities of choosing semidwarf varieties relative to those in the black soil zone, lower nitrogen rates in these two soil zones are foreseeable if farmers do apply more nitrogen to semidwarf wheat.

Although multiple sources have indicated the importance of rainfall in the performance of semidwarf wheat (e.g., Laing and Fischer 1977, Power and Alessi 1978), precipitation from the previous year does not have a meaningful effect on the choice of wheat varieties and nitrogen application rates. There are two sources of bias in the variable. First, a one-year lag may not be enough to capture farmer's expectation for the current year. Second, the precipitation data is collected by matching each field with its nearest weather station, which can be a coarse approximation. In our data, the distance from each field that grows wheat to its closest weather station ranges from 0.08 to 90 km. Weather data will lose precision for fields that are further away from its closest weather station.

Growing season temperature in the previous year, on the other hand, plays a much more important role in both decisions. When the previous growing season experienced high temperatures, farmers lean toward adopting semidwarf wheat in the current year. Yet, nitrogen application rates are expected to decrease by 2.1% when the average temperature in the previous growing season increases by 1°C. The coexistence of increased probabilities of adopting semidwarf wheat and decreased nitrogen application rates violates our expectation about the

Table 4.2: Coefficient estimates from the CF regression. Estimates of the probit model have been converted to marginal probabilities. Units of measurement are in squared brackets

Cut-off = Carberry (83cm)	*Dependent variable:*	
	Semidwarf 1st stage Probit	ln(Nitrogen) [lbs/ac] 2nd stage OLS
Stem rust resistance rating [1-5]	0.091***	
	(0.011)	
Leaf rust resistance rating [1-5]	0.26***	
	(0.022)	
Semidwarf		0.059***
		(0.004)
Soil zone: Brown	−0.13***	−0.23***
	(0.023)	(0.003)
Soil zone: Dark brown	−0.10***	−0.066***
	(0.014)	(0.002)
Total precipitation lag [mm]	-7.3e-05***	2.5e-05***
	(0.000)	(0.000)
Growing season mean temperature lag [Celsius]	0.058***	−0.021***
	(0.009)	(0.001)
Previous crop: Oilseed	0.014***	0.056***
	(0.013)	(0.002)
Previous crop: Pulse	0.019	−0.0057
	(0.112)	(0.015)
ln(Wheat price) [2019 Canadian dollar]	−0.14***	0.025**
	(0.095)	(0.010)
ln(Nitrogen price) [2019 Canadian Dollar]	0.28***	−0.0043
	(0.109)	(0.015)
ln(Expected yield) [Indexed with Carberry = 100]	−1.09***	0.34***
	(0.128)	(0.015)
Total liability [$1000 CAD]	1.9e-05***	8.0e-05***
	(0.000)	(0.000)
Year	0.048***	0.028***
	(0.005)	(0.001)
$\hat{r}$		−0.0085***
		(0.001)
Constant		−53***
		(1.442)
Observations	95,556	95,556

Statistical significance is denoted by: *p < 0.1; **p < 0.05; ***p < 0.01.

temperature effect. Nonetheless, this unexpected finding could be a result of the fact that the estimated 2.1% reduction in nitrogen rate is averaged across soil zones. It is likely that the effect of expected growing season temperature on nitrogen rates contains significant regional variation.

The crop rotation effects are estimated with the base level that a cereal crop was grown in the previous year. Growing an oilseed crop in the previous year only raises the probability of adopting semidwarf wheat by 1.4% compared to growing cereal crops in the previous year. For the nitrogen application rate, growing an oilseed in the previous year boosts the quantity of nitrogen fertilizer applied by 5.6% per acre compared to growing a cereal crop in the previous year. Growing pulse crops in the previous year increases the probability of choosing semidwarf wheat by 1.9% and decreases the nitrogen rate by around 0.6%, which is in line with the nitrogen-fixing properties of pulse crops. However, because neither of these two effects is statistically significant, interpretations should be made with caution.

Based on the estimated effect of expected yield, The expected yield of semidwarf wheat is about 1% lower than conventional wheat. One thing to notice is that the expected yields were collected from field tests that follow a uniform protocol (Saskatchewan Seed Growers Association 2022). In reality, the actual production of each variety will vary based on a number of factors, including weather and management practices. Moreover, semidwarf varieties can tolerate more nitrogen inputs without lodging. Thus, the comparison between yields of semidwarf and conventional wheat under a controlled experiment can be misleading. By applying nitrogen fertilizer in quantities that conventional wheat cannot endure, the actual yields of semidwarf varieties have great potential to be higher than conventional wheat.

To summarize, our model suggests that adopting semidwarf wheat is associated with higher nitrogen application rates. However, given the magnitudes of other coefficients, choosing semidwarf varieties is not the most important factor determining farmers' nitrogen use.

4.2.1 Robustness test for the Carberry cut-off

There exist possibilities that the Carberry cut-off does not effectively distinguish semidwarf and conventional wheat. For example, in the 2019 version of SaskSeed Guide (Saskatchewan Seed Growers Association 2019), which uses Carberry as the check variety of wheat, semidwarf wheat varieties AAC Starbuck and Cardale are 3 cm taller than Carberry. The existence of these varieties suggests that the actual cut-off height between semidwarf and conventional wheat could be taller than the Carberry cut-off. Hence, we increase this default cut-off height by 3 cm and 5 cm to test the sensitivity of our results to the cut-off.

When we use 86 cm (Carberry +3) as the cut-off (Table 4.3), there are $67,928$ and $27,628$ fields seeded with conventional and semidwarf wheat between 2011 and 2019. Under the Carberry cut-off, a total of $6,484$ more fields are classified as growing semidwarf wheat. Under this updated cut-off, the effect of growing semidwarf wheat on the nitrogen application rate decreases by 1.2 percentage points to 4.7%. The marginal effect of each instrument (resistance variables) in the first stage changed significantly compared to those under the Carberry cut-off; the marginal effect of stem rust resistance rating increased by about 10 percentage points, while the effect of leaf rust resistance rating decreased by about 19 percentage points. Other marginal effect estimates did not change by much from the Carberry cut-off.

Under the 88 cm (Carberry +5) cut-off (Table 4.4), 63,875 and 31,681 fields between 2011 and 2019 are classified as growing conventional and semidwarf wheat. A total of 10,537 fields are removed from "growing conventional wheat" to "growing semidwarf wheat" compared to the Carberry cut-off. The effect of growing semidwarf wheat on nitrogen application rate is 5.2% under the 88 cm cut-off, which has changed from the original estimate by less than 1 percentage point. The marginal effects of the instruments are again noticeably different from their original estimates. Similar to the 86 cm cut-off, other marginal effect estimates changed only by very small magnitudes.

Based on the results of two additional regressions, it seems that other than the instruments, the marginal effects of our regression variables change within a small and reasonable range. The effect of choosing semidwarf wheat on the nitrogen application rate—our key estimate in the second stage—stays around 5% under all cut-offs. Therefore, we conclude that our estimates are not very sensitive to the potential miscategorization of the two types of wheat.

Table 4.3: Coefficient estimates from the CF regression. Estimates of the probit model have been converted to marginal probabilities. Units of measurement are in squared brackets.

Cut-off = 86cm	*Dependent variable:*	
	Semidwarf 1st stage Probit	ln(Nitrogen) [lbs/ac] 2nd stage OLS
Stem Rust resistance rating [1-5]	0.19*** (0.011)	
Leaf Rust resistance rating [1-5]	0.067*** (0.007)	
Semidwarf		0.047*** (0.003)
Soil zone: Brown	−0.170*** (0.021)	−0.23*** (0.003)
Soil zone: Dark brown	−0.13*** (0.013)	−0.0064*** (0.002)
Total precipitation lag [mm]	-3.0e-05*** (0.000)	2.3e-05*** (0.000)
Growing season mean temperature lag [Celsius]	0.041*** (0.008)	−0.021*** (0.001)
Previous crop: Oilseed	0.010*** (0.012)	0.056*** (0.002)
Previous crop: Pulse	0.015 (0.102)	−0.0051 (0.015)
ln(Wheat price) [2019 Canadian dollar]	−0.066*** (0.077)	0.019* (0.010)
ln(Nitrogen price) [2019 Canadian dollar]	0.0036 (0.098)	−0.013 (0.015)
ln(Expected yield) [indexed with Carberry = 100]	−2.47*** (0.123)	0.37*** (0.016)
Total liability [$1000 CAD]	1.1e-05*** (0.000)	7.9e-05*** (0.000)
Year	0.049*** (0.005)	0.027*** (0.001)
$\hat{r}$		−0.0019** (0.001)
Constant		−52*** (1.443)
Observations	95,556	95,556

Statistical significance is denoted by: *p < 0.1; **p < 0.05; ***p < 0.01.

Table 4.4: Coefficent estimates from the CF regression. Estimates of the probit model have been converted to marginal probabilities. Units of measurement are in squared brackets.

Cut-off = 88cm	*Dependent variable:*	
	Semidwarf 1st stage Probit	ln(Nitrogen) [lbs/ac] 2nd stage OLS
Stem Rust resistance rating [1-5]	0.19*** (0.011)	
Leaf Rust resistance rating [1-5]	−0.030*** (0.006)	
Semidwarf		0.052*** (0.003)
Soil zone: Brown	−0.19*** (0.021)	−0.23*** (0.003)
Soil zone: Dark brown	−0.15*** (0.013)	−0.064*** (0.002)
Total precipitation lag [mm]	-3.4e-05*** (0.000)	2.3e-05*** (0.000)
Growing season mean temperature lag [Celsius]	0.056*** (0.008)	−0.021*** (0.001)
Previous crop: Oilseed	0.013*** (0.012)	0.056*** (0.002)
Previous crop: Pulse	0.026 (0.101)	−0.0060 (0.015)
ln(Wheat price) [2019 Canadian dollar]	−0.090*** (0.076)	0.011 (0.010)
ln(Nitrogen price) [2019 Canadian dollar]	0.12*** (0.099)	−0.024 (0.015)
ln(Expected yield) [indexed with Carberry = 100]	−2.64*** (0.125)	0.37*** (0.015)
Total liability [$1000 CAD]	2.2e-05*** (0.000)	7.9e-05*** (0.000)
Year	0.065*** (0.005)	0.026*** (0.001)
$\hat{r}$		−0.0025*** (0.001)
Constant		−50 (1.486)
Observations	95,556	95,556

Statistical significance is denoted by: *p < 0.1; **p < 0.05; ***p < 0.01.

4.3 Estimating direct N_2O emissions from synthetic nitrogen fertilizer applications

Given that semidwarf wheat affects direct N_2O emissions only through encouraging different fertilizer rates (Wang et al. 2021), as mentioned earlier, our estimation of N_2O emissions does not cover emission sources other than the application of synthetic nitrogen fertilizer.

4.3.1 Current fertilizer-induced direct N_2O emission status of wheat in Saskatchewan

The sample estimates of direct N_2O emissions from nitrogen fertilizer applied to Saskatchewan spring wheat are displayed in Table 4.5. The EF used for estimating emissions of spring wheat from the entirety of Saskatchewan is $0.0019\text{kg}\,N_2O{-}N\,\text{kg}^{-1}\,N$ (Rochette et al. 2018). Within our sample, every tonne of conventional wheat produced in Saskatchewan is associated with $28.8 - 39.46$ kg CO_2eq of fertilizer-induced direct N_2O emissions, and this number lies between 29.01 and 41.84 kg CO_2eq for semidwarf wheat in the province.

Although our previous econometric analysis suggests that farmers tend to use more nitrogen with semidwarf wheat relative to conventional wheat, semidwarf wheat does not always have a higher emission per tonne of production compared to conventional wheat based on our estimation. The trends in emission per tonne indeed change back and forth for both types of wheat over the year, and semidwarf wheat turns out to have lower emissions per tonne of production relative to conventional wheat in more recent years. An explanation for this observation is that the yields of wheat are increasing faster than changes in nitrogen use. The high yield of semidwarf wheat makes the ratio of emission versus yield small. However, given the expanding acreage of semidwarf wheat in Saskatchewan, the total emission of semidwarf wheat could still be higher than conventional wheat.

In addition, as Saskatchewan can be divided into three soil zones (Figure 3.2), we use soil zone-specific EFs to compare estimates with and without considering variation in soil characteristics. Estimates for the black soil zone and brown plus dark brown soil zones are shown in Tables 4.6 and 4.7. According to Rochette et al. (2018), the black soil zone has an EF of 0.0033kg $N_2O{-}N\,kg^{-1}\,N$, while the brown and dark brown soil zones have the same EF of 0.0016kg $N_2O{-}N\,kg^{-1}\,N$. In the black soil zone of Saskatchewan, the fertilizer-induced direct N_2O emissions per tonne of production range between $49.98 - 69.06$ and $50.22 - 74.43$ kg CO_2eq for conventional and semidwarf wheat, respectively. In brown and dark brown soil zones, every tonne of conventional and semidwarf wheat produced is linked to $24.34 - 33.25$ and $24.63 - 32.97$ kg CO_2eq of fertilizer-induced direct N_2O emissions. Under these alternative EFs, similar to the previous EF that does not distinguish soil zones, semidwarf wheat sometimes introduces less fertilizer-induced direct N_2O emission per tonne of grain yield than conventional wheat. The black soil zone experiences higher per-tonne emissions relative to the other two soil zones, which is mostly caused by the difference in EFs.

Meanwhile, from other studies that cover more emission sources in wheat production, we can make inferences about what the expected range of per-tonne fertilizer-induced direct N_2O emissions might be. For instance, according to ECCC (2021b), the mean value of N_2O emissions from agricultural soils in Canada is 24 Mt CO_2eq. After including emissions from manure management, the mean N_2O emission in the Canadian agricultural sector is 28 Mt CO_2eq. The mean value of direct N_2O emissions induced by nitrogen fertilizer application is about 39% of direct N_2O emissions from all sources summed together. Therefore, we can form a very coarse expectation about the quantity of fertilizer-induced direct N_2O emission from this expected share. For example, Canadian Roundtable on Sustainable Crops (2017) reports that the N_2O emission per tonne of wheat production in Saskatchewan ranges between $130.9 - 204.6$ kg CO_2eq tonne^{-1}. Using the 39% expected share, the fertilizer-induced direct N_2O emission would range between $51.1 - 79.8$ kg CO_2eq tonne^{-1}. In our estimates of emissions, only estimates for the black soil zone (Table 4.6) fall within this range[1]. Estimates made for other two regions (Tables 4.5 and 4.7) are a lot smaller compared to this range. However, it should be noticed that ECCC (2021b), Canadian Roundtable on Sustainable Crops (2017),

[1]The explicit estimates for emission per tonne of production in Tables 4.5-4.7 can be found in Appendix A. Note that our emission estimates do not represent all fertilizer-induced direct N_2O emissions from spring wheat in Saskatchewan as there are farms that did not participate in the survey, and some varieties are not included due to missing data

and this study use different EFs. The time spans and test regions are also different. Therefore, directly comparing estimations of emissions from different studies may not be very informative.

When plotting the N_2O emission per tonne of production (Figure 4.5), we see no overall upward or downward time trends for any soil zone specifications, indicating that the per-tonne fertilizer-induced direct N_2O emission does not increase in the same rate as the acreage of semidwarf wheat. Nevertheless, it is worth noting that although the black soil zone is just a partition of Saskatchewan, because it has a higher EF, its estimated emissions per-tonne of production are greater than those for the entirety of Saskatchewan. This finding suggests that using one EF for the province as a whole may underestimate the actual emissions.

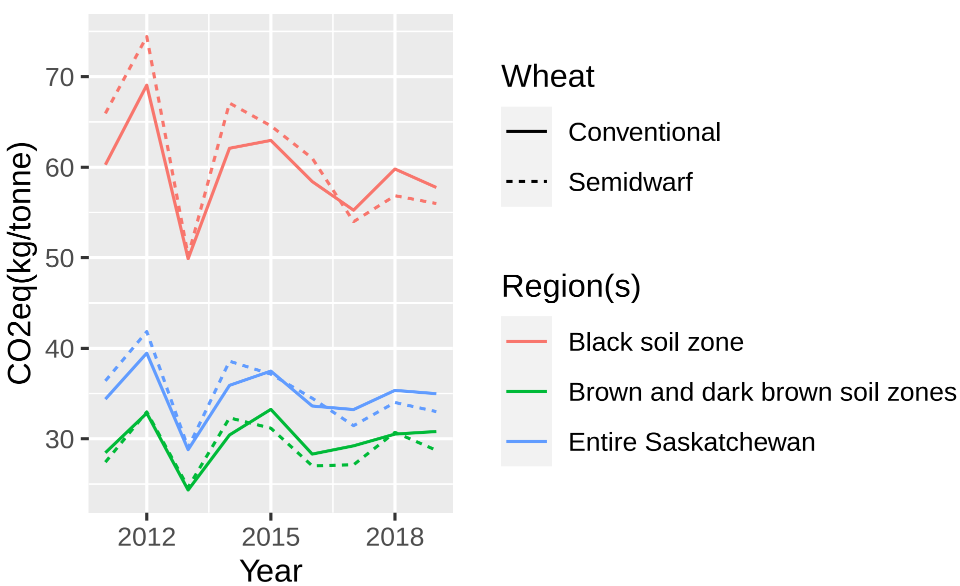

Figure 4.5: Time trends in fertilizer-induced N_2O emissions of spring wheat in Saskatchewan and its soil zones between 2011 and 2019

Table 4.5: Estimates of direct N_2O emissions from nitrogen fertilizer applied to spring wheat in Saskatchewan for SCIC sample regions.

Year	Wheat	Sample production (tonne)	Direct CO_2eq (kg)	Direct CO_2eq (kg/tonne)*
2011	Conventional	622,696.19	21,410,567.19	34.38
	Semidwarf	68,638.24	2,498,687.49	36.40
2012	Conventional	1,086,834.6	42,886,680.12	39.46
	Semidwarf	104,683.58	4,379,672.21	41.84
2013	Conventional	2,029,482.75	58,450,868.81	28.80
	Semidwarf	289962.81	8412378.27	29.01
2014	Conventional	1,521,669.68	54,630,623.64	35.90
	Semidwarf	254,479.91	9,814,160.13	38.57
2015	Conventional	1,278,548.75	47,914,849.16	37.48
	Semidwarf	369,412.38	13,721,473.57	37.14
2016	Conventional	1,014,691.69	34,116,793.16	33.62
	Semidwarf	500,088.08	17,244,111.68	34.48
2017	Conventional	1,088,586.74	36,172,313.94	33.23
	Semidwarf	900,118.14	28,306,954.78	31.45
2018	Conventional	929,758.92	32,864,137.42	35.35
	Semidwarf	1,421,732.94	48,348,529.82	34.01
2019	Conventional	597,254.68	20,889,151.17	34.98
	Semidwarf	1,967,608.15	64,939,828.81	33.00

Notes:
EF = 0.0019 (Rochette et al. 2018) for Saskatchewan as a whole.
$*$per ton grain production

Table 4.6: Estimates of direct N_2O emissions from nitrogen fertilizer applied to spring wheat in Saskatchewan for SCIC sample regions in the black soil zone.

Year	Wheat	Sample production (tonne)	Direct CO_2eq (kg)	Direct CO_2eq (kg/tonne)*
2011	Conventional	403,189.61	24,301,512.27	60.27
	Semidwarf	48,802.15	3,218,187.88	65.94
2012	Conventional	660,634.98	45,624,551.39	69.06
	Semidwarf	75,935.39	5,652,167.73	74.43
2013	Conventional	1,168,533.95	58,293,174.91	49.89
	Semidwarf	205,380.97	10,314,280.53	50.22
2014	Conventional	907,008.78	56,314,828.82	62.09
	Semidwarf	196,822.18	13,203,069.56	67.08
2015	Conventional	793,831.63	49,977,645.61	62.96
	Semidwarf	293,959.24	18,981,434.17	64.57
2016	Conventional	593,291.18	34,652,024.68	58.41
	Semidwarf	395,694.49	24,134,048.68	60.99
2017	Conventional	553,707.4	30,593,258.99	55.25
	Semidwarf	605,739.86	32,695,516.4	53.98
2018	Conventional	458,315.63	27,407,016.65	59.80
	Semidwarf	936,058.86	53,214,167.16	56.85
2019	Conventional	287,962	16,633,041.32	57.76
	Semidwarf	1,162,318.18	65,077,735.71	55.99

Notes:
EF = 0.0033 for the black soil zone (Rochette et al. 2018).

Table 4.7: Estimates of direct N_2O emissions from nitrogen fertilizer applied to spring wheat in Saskatchewan for SCIC sample regions in brown and dark brown soil zones.

Year	Wheat	Sample production (tonne)	Direct CO_2eq (kg)	Direct CO_2eq (kg/tonne)*
2011	Conventional	219,506.58	6,247,399.91	28.46
	Semidwarf	19,836.1	543,824.37	27.42
2012	Conventional	426,199.63	13,994,104.43	32.83
	Semidwarf	28,748.18	947,700.05	32.97
2013	Conventional	860,948.8	20,958,426.73	24.34
	Semidwarf	84,581.85	2,083,244.73	24.63
2014	Conventional	614,660.9	18,700,576.27	30.42
	Semidwarf	57,657.74	1,863,067.63	32.31
2015	Conventional	484,717.12	16,117,760.91	33.25
	Semidwarf	75,453.14	2,351,805.52	31.17
2016	Conventional	421,400.5	11,928,949.42	28.31
	Semidwarf	104,393.59	2,820,000.26	27.01
2017	Conventional	534,879.34	15,627,800.68	29.22
	Semidwarf	294,378.28	7,985,064.01	27.13
2018	Conventional	471,443.3	14,386,812.59	30.52
	Semidwarf	485674.09	14913743.11	30.71
2019	Conventional	309,292.68	9,526,359.26	30.80
	Semidwarf	805,289.98	23,133,330.07	28.73

Notes:
EF = 0.0016 for brown and dark brown soil zones (Rochette et al. 2018).

4.3.2 The effects of adopting semidwarf wheat on direct N_2O emissions

In this subsection, we use sample estimates to predict fertilizer-induced direct N_2O emissions of spring wheat at the provincial level of Saskatchewan. We calculate changes in emissions in five hypothetical scenarios: when the acreages of conventional and semidwarf wheat in Saskatchewan are at the status quo, and when $20, 50, 80, 100$ percent of the remaining conventional wheat acres are replaced with semidwarf wheat. In light of the fact that Saskatchewan is in a transitioning period from conventional to semidwarf wheat varieties, this experiment predicts how direct N_2O emissions from nitrogen fertilizer application will change as conventional wheat acres are gradually replaced by semidwarf varieties. The emissions in each scenario are calculated for (1) the entirety of Saskatchewan, (2) the black soil zone, and (3) brown plus dark brown soil zones with their respective EFs provided in Rochette et al. (2018). We use emissions estimated for 2019 as the status quo as it is the most recent record in our sample.

To predict emissions at the provincial level, we assume that our sample is representative of all spring wheat fields in Saskatchewan, and the sample distribution of soil zones is also representative of the real soil zone distribution in Saskatchewan. According to Statistics Canada (2019), in 2019, Saskatchewan farmers reported $8,700,000$ acres of spring wheat in the province, while our sample records $1,750,150$ acres. The ratio between spring wheat acres in the sample and at the population level is $1,207/6,000$ (approximately 1:5). With this sample-population ratio, we can extend the estimation of emissions made within the sample to all spring wheat acres in Saskatchewan in each of the five scenarios we consider. Based on Equation 3.11, we develop the following steps for calculating emissions at the provincial level.

First, the status-quo emissions are calculated within sample as

$$N_2O^o_{wheat} = \sum_i Acres_{wheat,i} \times N_{wheat,i} \times EF \times \frac{48}{22} \times 298 \qquad (4.1)$$
$$wheat \in \{sem, con\},$$

where the subscript *wheat* can be either *sem* or *con*, representing semidwarf or conventional wheat varieties. Subscript i denotes each field in the sample whose variety type is given by *wheat*, and the superscript o indicates that this variable measures emissions at the status quo. $N_2O^o_{wheat}$ is the status-quo fertilizer-induced direct N_2O emission of wheat variety indicated by *wheat* within sample. $Acres_{wheat,i}$ is the acreage of each individual field that grows varieties denoted by *wheat* in the sample. $N_{wheat,i}$ is the actual nitrogen rate (kg/acre) of each field that grows varieties indicated by *wheat* in the sample. EF is the emission factor of nitrogen fertilizer, the value of which varies across soil zone specifications. The multiplier 48/22 converts $N_2O{-}N$ to N_2O, and the another multiplier 298 converts N_2O to CO_2eq.

With the status quo emissions calculated using Equation 4.1, the provincial-level emissions of semidwarf wheat are calculated as

$$N_2O_{sem} = \frac{N_2O^o_{sem} + Acres_{con} \times t \times EXPN \times EF \times \frac{48}{22} \times 298}{R \times 1000}, \quad (4.2)$$

where N_2O_{sem} is the provincial-level fertilizer-induced direct N_2O emission from semidwarf wheat. $N_2O^o_{sem}$ is the fertilizer-induced direct N_2O emission of semidwarf wheat at the status quo within our sample calculated using Equation 4.1. Scalar $t \in [0, 1]$ is the proportion of conventional wheat acres switched to semidwarf wheat. For example, in the scenario that 20% of the remaining conventional wheat acres in Saskatchewan have switched to semidwarf wheat, $t = 0.2$. $EXPN$ is the expected nitrogen application rate measured in kg/acre of fields that switched to semidwarf wheat from conventional varieties. It is calculated as the average nitrogen rate of conventional wheat in 2019 multiplied by (1 + 5.9%), where 5.9% is the marginal effect of switching from conventional to semidwarf wheat on the nitrogen rate estimated by our regression model. The mean nitrogen rate of conventional wheat in 2019 is 83.9 lbs per acre in our sample. Thus, fields that switched from conventional to semidwarf wheat are set to have a nitrogen rate of 88.8 lbs per acre in our experiment, which translates to 40.36 kg/acre. Finally, R in the denominator is the ratio $1,207/6,000$ for converting sample estimates to provincial-level estimates. The multiplier $1,000$ converts the final output unit to tonnes CO_2eq. Other parameters are defined in the same way as in Equation 4.1.

Next, the emissions of conventional varieties are calculated as

$$N_2O_{con} = \frac{N_2O^o_{con} \times (1-t)}{R \times 1000}, \tag{4.3}$$

where N_2O_{con} is the provincial-level fertilizer-induced direct N_2O emission from conventional wheat. $N_2O^o_{con}$ is the fertilizer-induced direct N_2O emission from conventional wheat at the status quo within our sample. Other parameters are defined the same as Equation 4.1 and Equation 4.2.

Equations 4.1-4.3 are calculated with three sub-samples of our full sample. Each sub-sample is a partition of the full sample according to one of the three soil zone specifications: the entirety of Saskatchewan, the black soil zone, and brown plus dark brown soil zones. The parameter EF needs to vary to be aligned with the soil zone specification of each sub-sample. Therefore, results are also grouped by soil zone specifications.

The predicted total fertilizer-induced direct N_2O emissions are in Table 4.8. At the status quo for the entirety of Saskatchewan (0% change), the total fertilizer-induced direct N_2O emission from spring wheat is about 427 thousand tonnes CO_2eq, about 76% of which are attributed to semidwarf varieties. When 20% of the conventional wheat acres in the province have switched to semidwarf wheat, the total emission increases by $1,142.35$ tonnes CO_2eq, which is an increase of about 0.27% from the status quo. If all remaining conventional wheat acres in the province are replaced by semidwarf wheat, the total fertilizer-induced direct N_2O emission will jump to 432 thousand tonnes CO_2eq.

When using a distinct EF for each soil zone in Saskatchewan, 70.9% of the total fertilizer-induced direct N_2O emissions come from the black soil zone. Estimated emissions for the black soil zone alone are almost the same size as those estimated for the entirety of Saskatchewan using the uniform EF. This is not hard to explain given that the black soil zone has most of the spring wheat acres in Saskatchewan (see Table 4.1 and Figure 4.1) and a relatively higher EF (Rochette et al. 2018). If all remaining conventional wheat acres at the status quo of Saskatchewan have switched to semidwarf wheat, the total fertilizer-induced direct N_2O emission calculated using soil zone-specific EFs is about 141 thousand tonnes CO_2eq greater than the estimation under a uniform EF for the entire province. This discrepancy further demonstrates the importance of finding EFs that are as specific to the local geological conditions as possible.

To get a sense of the contribution of the fertilizer-induced direct N_2O emission from spring wheat to the overall GHG emission in Saskatchewan, we compare our experimental emissions to the total GHG emission of 75 million tonnes in Saskatchewan in 2019 (ECCC 2021b). Under the uniform EF for the entirety of Saskatchewan, the hike in nitrogen rates after switching all conventional wheat to semidwarf wheat would increase the total GHG emission of the province by 0.008%. When we use soil zone-specific EFs, the total GHG emission of Saskatchewan is expected to increase by 0.006% when all remaining conventional wheat has switched to semidwarf wheat.

The valuation of environmental damage caused by the fertilizer-induced direct N_2O emission from Saskatchewan spring wheat is provided in Table 4.9. We use SCC—the social cost of carbon per unit of GHGs emitted—to estimate the damage caused by N_2O emissions. ECCC (2020) suggests a SCC of \$50 CAD tonne^{-1} CO_2eq. In 2019, the fertilizer-induced direct N_2O emission of spring wheat in Saskatchewan is valued at \$21.33 million CAD using the uniform EF. When 20% of the remaining conventional wheat acres have switched to semidwarf wheat, the value of environmental damage would increase by \$0.06 million CAD. If all remaining conventional wheat in Saskatchewan has become semidwarf wheat, an additional value of \$0.29 million CAD would be added to the existing environmental damage introduced by the nitrogen fertilizer applied to spring wheat in Saskatchewan.

Table 4.8: Estimated fertilizer-induced direct N_2O emissions (tonnes CO_2eq) of spring wheat in Saskatchewan in 2019 when a portion of conventional wheat acres switches to semidwarf wheat.

		Percentage of remaining conventional wheat acres switching to semidwarf wheat				
Area(s)	Wheat	0	20	50	80	100
Saskatchewan						
	Conventional	103,840.02	83,072.02	51920.01	20768	0
	Semidwarf	322,816.05	344,726.40	377,591.94	410,457.47	432,367.82
	Total	426,656.07	427,798.42	429,511.95	431,225.47	432,367.82
Black soil zone						
	Conventional	82,682.89	66,146.31	41,341.44	16,536.58	0
	Semidwarf	323,501.59	340,066.22	364,913.18	389,760.14	406,324.78
	Total	406,184.48	406,212.54	406,254.63	406,296.72	406,324.78
Brown & dark brown soil zones						
	Conventional	47,355.56	37,884.44	23,677.78	9,471.11	0
	Semidwarf	114,995.84	125,415.33	141,044.55	156,673.78	167,093.27
	Total	162,351.4	163,299.77	164,722.33	166,144.89	167,093.27

Notes:
EF = 0.0019 (Rochette et al. 2018) for Saskatchewan as a whole.
EF = 0.0033 for black soil zone (Rochette et al. 2018).
EF = 0.0016 for brown and dark brown soil zones (Rochette et al. 2018).

Similar to the previous estimation of N_2O emissions, when soil zone-specific EFs are considered, the black soil zone produces most of the environmental damage of fertilizer-induced direct N_2O emissions. When using different EFs for soil zones in Saskatchewan, the two types of wheat together introduce fertilizer-induced direct N_2O emissions that are valued at \$28.43 million CAD at the status quo, which is \$7.1 million CAD more than the value estimated using the uniform EF across the province. When 100% of the remaining conventional wheat acres in Saskatchewan are replaced with semidwarf wheat, the associated environmental damage from fertilizer-induced direct N_2O emissions is valued at \$28.67 million CAD when soil zone-specific EFs are used, while this value is \$21.62 million CAD under the uniform EF.

To compare our valuation of the N_2O emissions with the current carbon pricing policies of Canada, the environmental damage valuation is reproduced with the carbon price provided by the Government of Canada (2021b) (Table 4.10). The Government of Canada (2021b) proposed to increase the carbon pollution pricing to \$170 CAD tonne^{-1} CO_2eq by 2030. Using this carbon price as the value of the damage caused by GHGs, the environmental damage of fertilizer-induced direct N_2O emissions of spring wheat in Saskatchewan is valued at \$72.53, \$69.05, and \$27.6 million CAD for the entirety of Saskatchewan, the black soil zone alone, and brown plus dark brown soil zones at the status quo. When using the uniform EF for Saskatchewan as a whole under the proposed carbon price, the environmental damage of fertilizer-induced direct N_2O emissions of spring wheat increases to \$73.5 million CAD if 100% of the remaining conventional wheat acres have switched to semidwarf wheat. This number is greater than its counterfactual under the ECCC (2020) value of SCC by \$51.88 million CAD. With soil zone-specific EFs, the damage of direct N_2O induced by nitrogen fertilizer applied to spring wheat evaluated under the proposed carbon price increases to \$97.49 million CAD when all of the remaining conventional wheat in the province has switched to semidwarf wheat. In contrast, the same damage is valued at \$28.67 million CAD using the SCC provided by ECCC (2020), which is \$68.82 million CAD smaller than using the carbon price provided by the Government of Canada (2021b). However, it is important to note that the valuation using carbon pollution pricing may not be representative of the actual environmental damage, given that the carbon price is not necessarily aligned with SCC.

Considering the impact of N_2O emissions on the global scale, we also valuate the environmental damage with the global social cost of carbon (GSCC). GSCC is calculated by aggregating country-level SCCs. We use GSCC=417 USD tonne^{-1} CO_2eq estimated by Ricke et al. (2018) under the assumption that the social, economic, and technological trends of the world follow their historical patterns. It is converted to GSCC $\approx$ 553 CAD tonne^{-1} CO_2eq using the exchange rate of \$1.3269 CAD/USD of 2019 (Bank of Canada 2021). The valuation of the environmental damage using GSCC is in Table 4.11. Under the status quo with the uniform EF, the fertilizer-induce direct N_2O emission of Saskatchewan spring wheat causes damage valued at \$236.08 million CAD to the world, which is more than 10 folds of the cost introduced to Canada under the same EF (Table 4.9). When all of the remaining conventional wheat acres in Saskatchewan are replaced by semidwarf varieties, under the uniform EF for the whole province, the value of environmental damage associated with fertilizer-induced direct N_2O emissions increases by \$3.16 million CAD to \$239.24 million CAD. Under soil zone-specific EFs, the environmental damage of fertilizer-induced direct N_2O emission of Saskatchewan spring wheat is valued at \$314.58 million CAD at the status quo, and this number will increase to \$317.29 million CAD when all remaining conventional wheat acres in Saskatchewan have switched to semidwarf wheat.

It is important to consider some caveats before drawing conclusions from these results. First, the value of SCC is consistently being updated. For instance, the Environmental Protection Agency (EPA) of the U.S. put forward a significant cut to the cost of carbon in 2017 in its proposal to repeal the Clean Power Plan, changing the original SCC of \$47 USD $tonne^{-1}$ CO_2eq to somewhere between \$1 and \$6 USD (The Economist 2017). In addition, recent research undertaken by Rennert et al. (2022) suggests a social cost of \$185 USD $tonne^{-1}$ CO_2eq, which 3.6 time higher than the current value of \$51 USD $tonne^{-1}$ CO_2eq. Such events may challenge the validity of the SCC used by the ECCC (2020), given that the ECCC adopts analysis conducted by the U.S. Interagency Working Group on SCC. Indeed, SCC is likely to move higher (as opposed to lower) though that could be vulnerable to regulatory changes depending on the government in power. Second, despite the two-round robustness tests, the cut-off height of semidwarf and conventional wheat (83 cm) is only an approximation to the true cut-off height. However, it does become the most effective way when detailed genome structures are not available to us. Furthermore, the scope of this study is rather narrow; it only covers the direct emission from soil nitrogen inputs. Thus, changes in carbon dioxide are not considered, and any inference made in this study should not be passed onto other wheat categories without further testing.

Table 4.9: Estimated total social cost (million CAD) from fertilizer-induced direct N_2O emissions produced in Saskatchewan wheatland in 2019 when a portion of conventional wheat acres switches to semidwarf wheat. SCC = \$50 CAD tonne^{-1} CO_2eq

		Percentage of remaining conventional wheat acres switching to semidwarf wheat				
Area(s)	Wheat	0	20	50	80	100
Saskatchewan						
	Conventional	5.19	4.15	2.6	1.04	0
	Semidwarf	16.14	17.24	18.88	20.52	21.62
	Total	21.33	21.39	21.48	21.56	21.62
Black soil zone						
	Conventional	4.13	3.31	2.07	0.83	0
	Semidwarf	16.18	17	18.25	19.49	20.32
	Total	20.31	20.31	20.31	20.31	20.32
Brown & dark brown soil zones						
	Conventional	2.37	1.89	1.18	0.47	0
	Semidwarf	5.75	6.27	7.05	7.83	8.35
	Total	8.12	8.16	8.24	8.31	8.35

Notes:
EF = 0.0019(Rochette et al. 2018) for Saskatchewan as a whole.
EF = 0.0033 for black soil zone(Rochette et al. 2018).
EF = 0.0016 for brown and dark brown soil zones(Rochette et al. 2018).
SCC = \$50 CAD tonne^{-1} CO_2eq (ECCC 2020).

Table 4.10: Estimated total social cost (million CAD) from fertilizer-induced direct N_2O emissions produced in Saskatchewan wheatland in 2019 when a portion of conventional wheat acres switches to semidwarf wheat. SCC = \$170 CAD tonne^{-1} CO_2eq

		Percentage of remaining conventional wheat acres switching to semidwarf wheat				
Area(s)	Wheat	0	20	50	80	100
Saskatchewan						
	Conventional	17.65	14.12	8.83	3.53	0
	Semidwarf	54.88	58.6	64.19	69.78	73.5
	Total	72.53	72.73	73.02	73.31	73.5
Black soil zone						
	Conventional	14.06	11.24	7.03	2.81	0
	Semidwarf	55	57.81	62.04	66.26	69.08
	Total	69.05	69.06	69.06	69.07	69.08
Brown & dark brown soil zones						
	Conventional	8.05	6.44	4.03	1.61	0
	Semidwarf	19.55	21.32	23.98	26.63	28.41
	Total	27.6	27.76	28	28.24	28.41

Notes:
EF = 0.0019(Rochette et al. 2018) for Saskatchewan as a whole.
EF = 0.0033 for black soil zone(Rochette et al. 2018).
EF = 0.0016 for brown and dark brown soil zones(Rochette et al. 2018).
SCC = \$170 CAD tonne^{-1} CO_2eq (Government of Canada 2021b).

Table 4.11: Estimated total GSCC (million CAD) from fertilizer-induced direct N_2O emissions produced in Saskatchewan wheatland in 2019 when a portion of conventional wheat acres switches to semidwarf wheat. Per-unit GSCC $\approx$ \$553 CAD tonne^{-1} CO_2eq

		Percentage of remaining conventional wheat acres switching to semidwarf wheat				
Area(s)	Wheat	0	20	50	80	100
Saskatchewan						
	Conventional	57.46	45.97	28.73	11.49	0
	Semidwarf	178.62	190.74	208.93	227.11	239.24
	Total	236.08	236.71	237.66	238.6	239.24
Black soil zone						
	Conventional	45.75	36.6	22.87	9.15	0
	Semidwarf	179	188.16	201.91	215.66	224.83
	Total	224.75	224.76	224.79	224.81	224.83
Brown & dark brown soil zones						
	Conventional	26.2	20.96	13.1	5.24	0
	Semidwarf	63.63	69.39	78.04	86.69	92.46
	Total	89.83	90.36	91.14	91.93	92.46

Notes:
EF = 0.0019(Rochette et al. 2018) for Saskatchewan as a whole.
EF = 0.0033 for black soil zone(Rochette et al. 2018).
EF = 0.0016 for brown and dark brown soil zones(Rochette et al. 2018).
GSCC = \$417 USD tonne^{-1} CO_2eq (Ricke et al. 2018).
GSCC is converted to CAD using the 2019 exchange rate of \$1.3269CAD/USD (Bank of Canada 2021).

Chapter 5

Conclusion

By regressing the adoption of semidwarf wheat and the use of nitrogen fertilizer, this study found a 5.9% increase in the fertilizer application rate when a Saskatchewan wheat farmer switches from conventional to semidwarf varieties. Further robustness tests suggest that our results are consistent over a wide threshold of the cut-off height between semidwarf and conventional wheat. Despite that the choice between semidwarf and conventional wheat has a non-negligible impact on the nitrogen application rate, it is far from the only factor that determines the final nitrogen application rate. Field characteristics such as soil zones and crop rotations can potentially affect farmers' decisions on fertilizer more than wheat varieties themselves. While semidwarf wheat is expected to have higher nitrogen application rates than conventional wheat, its yield benefit is also prominent. The average annual production rates of semidwarf wheat in Saskatchewan between 2011 and 2019 are higher than those of conventional wheat by 0.17, 0.14, 0.15 tonnes per acre in black, brown, and dark brown soil zones (Table 4.1).

The subsequent analysis for N_2O suggests an upward trajectory for direct N_2O emissions induced by nitrogen fertilizer applications as semidwarf wheat varieties gradually replace conventional varieties in the province. On the other hand, the emission per tonne of grain yield is similar across the two varieties types. For example, in 2019, the direct N_2O emissions caused by nitrogen fertilizer are 34.98 and 33 kg CO_2eq per tonne of semidwarf and conventional wheat produced using the uniform EF for the entirety of Saskatchewan (Table 4.5). This similarity reflects the high production of semidwarf wheat, despite that it is associated with higher nitrogen inputs. In the absence of policies that disincentivize the use of nitrogen fertilizer, we expect the upward trend in fertilizer-induced direct N_2O emissions of semidwarf wheat to continue because its high yield will keep facilitating its adoption.

By the time all remaining conventional wheat in Saskatchewan is replaced with semidwarf wheat, the value of environmental damage caused by fertilizer-induced direct N_2O emissions would increase by at least \$0.29 millions of CAD. On the other hand, given the 2019 average wheat price in Saskatchewan of \$231.89 CAD per tonne (Statistics Canada 2022), and the 13% increase in production rate when switching from conventional to semidwarf wheat that we estimated previously, the total revenue of Saskatchewan wheat farmers in 2019 will increase by about \$90 million CAD if all remaining conventional wheat acres are replaced with semidwarf wheat[1]. This comparison suggests that producers' marginal benefit of adopting semidwarf wheat greatly exceeds the environmental externality from the increase in direct N_2O emissions. Therefore, we may conclude that adopting semidwarf wheat is an overall very beneficial decision for Saskatchewan farmers. However, this should not be seen as evidence that the environmental effects are not important when evaluating the benefit and cost of adopting semidwarf varieties. It is important to note that the costs of environmental damages cannot be perfectly measured by money or any other metrics that are only meaningful in human society.

In summary, even though semidwarf wheat varieties provide higher yields and potentially more revenues for farmers, our results suggest that the adoption of these varieties is followed by higher N_2O emissions due to increased nitrogen inputs. To consider this trade-off when adopting semidwarf wheat, if the agricultural sector plans to mitigate GHG emissions of semidwarf varieties, perhaps more genetic research is needed to increase the nitrogen-use efficiency of the more popular semidwarf varieties. In addition, implying the 4R management (right source, right rate, right time, and right place) to reduce the negative social impact of fertilizer application and adopting efficient crop rotation patterns to reduce nutrient waste will also help mitigate the problem of N_2O emission in the agricultural sector.

[1] The 2019 production of conventional wheat in Saskatchewan is approximated by dividing the sample production of $597,254.68$ tonnes of conventional wheat by the sample-population ratio of $1,207/6,000$. Under this calculation, roughly $385,964.08$ tonnes of extra yield are expected when all remaining conventional wheat acres switch to semidwarf wheat.

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Appendix A

Formula for calculating N_2O emission per tonne of grain production in Tables 4.5-4.7

The fertilizer-induced direct N_2O emitted per tonne of grain production is calculated using the following formula:

$$ANE_{area,year} = \frac{TNE_{area,year}}{Q_{area,year}}, \tag{A.1}$$

where *area* denotes the soil zone in which the equation is used for (The entirety of Saskatchewan, the black soil zone, and brown plus dark brown soil zones), and *year* denotes the year of production. ANE represents the average fertilizer-induced direct N_2O emission measured in kg CO_2eq per tonne of grain production, TNE is the total fertilizer-induced direct N_2O emission in tonne calculated using Equation 3.11.

$Q_{area,year}$ is total grain production from the sample indicated by the subscripts of Q, measured in tonne. Note that TNE and $Q_{area,year}$ are totals within the sample, not all spring wheat in Saskatchewan.

For example, in the first row of Table 4.6, the fertilizer-induced direct N_2O emission per tonne of conventional wheat production in the black soil zone in 2011 is calculated as:

$$ANE_{black,2011} = \frac{24,301,512.27}{403,189.61} = 60.27\,\mathrm{kg\,CO_2eq\,tonne^{-1}}, \qquad \text{(A.2)}$$

where $TNE_{black,2011} = 21,610.41$ is derived from Equation 3.11 in the following way:

$$TNE_{black,2011} = \frac{\sum_i (\mathrm{N}_{black,2011,i} \times 0.0033 * 1) \times \frac{48}{22} \times 265}{1000}. \qquad \text{(A.3)}$$

Index i represents each field in the sample that produces wheat in the black soil zone of Saskatchewan in 2011. N is the quantity of nitrogen fertilizer applied in kg. The emission factor of nitrogen fertilizer in the black soil zone is 0.0033kg $\mathrm{N_2O{-}N\,kg^{-1}\,N}$ according to Rochette et al. (2018). The ratio 48/22 is a coefficient for converting $\mathrm{N_2O{-}N}$ to N_2O. The multiplier 265 (adopted from IPCC Working Group I's fifth report (2007)) converts the measurement unit from kg N_2O to kg CO_2eq. The whole expression is divided by 1000 to convert the unit of output to tonnes CO_2eq.