Assessment of greenhouse gas emissions from soybean cropping system: A case study of Ontario in Canada

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ABSTRACT

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Marjan Esbati

Soybean (*Glycine max* L.) is the fourth largest Canadian field crop covering around 2×10^6 hectares of land. Soybean crops take up more than 50% of Canada's cultivated areas and contribute significantly to greenhouse gas (GHG) emissions in cropping system. The present study assesses GHG emissions from Ontario soybean fields. In this study, the crop districts of Ontario were divided into five categories: southern Ontario, western Ontario, central Ontario, eastern Ontario, and northern Ontario, and a general model for assessing emissions was developed. Emissions from the manufacturing and transportation of nitrogen/phosphorus (N/P) fertilizer, emissions from field operations, emissions from herbicide usage, and both direct and indirect emissions from agricultural lands were considered the major sources of GHGs. The results showed that total GHG emissions were around 7×10^5 Mg CO_2-eq in 2018. The largest emission contributor was agricultural land, with emissions of 5.3×10^5 Mg CO_2-eq, accounting for 77% of the total emissions. Moreover, GHG emissions were significantly influenced by environmental conditions. As precipitation/evapotranspiration (Pr/PE) decreased, total GHG emissions declined from southern Ontario to central Ontario. In southern Ontario (high Pr/PE), GHG emissions based on crop yield were 492 kg CO_2-eq per hectare of seeding area, which was 46% greater than those in northern Ontario (low Pr/PE). GHG emissions from agricultural lands were the highest contributor to total GHG emissions among the four emission sources in all crop districts. Fertilizer N inputs accounted for the largest portion of agricultural land emissions in southern and central Ontario, while in other regions, crop residue N input was the largest source. A multivariate factorial analysis was also used to estimate the effect of uncertain parameters on system performance, and the main impacts, and their interactions were identified. The resutls demonstrated that farming practices had the most significant impact on total GHG emissions. Understanding the detailed impacts of these elements and their interactions can help determine major factors that influence total GHG emissions and allow us to implement appropriate strategies to mitigate agricultural GHG emissions.

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DEDICATION

This work is dedicated to my beloved parents.

Mrs. Maryam Rezaei

Mr. Hossein Esbati

Most importantly, I am greatly indebted to the consistent support of my parents, who have silently sacrificed so much to provide me with the foundations necessary to pursue higher education. They provided me with their unconditional love in every possible way. Their belief and faith in me have given me enormous strength and courage to accomplish my goals.

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LIST OF ABBREVIATIONS

CO_2	Carbon Dioxide
N_2O	Nitrous Oxide
GHG	Greenhouse Gas
CFI	Carbon Farming Initiative
N	Nitrogen
P	Phosphorous
SGER	Specified Gas Emitters Regulation
CH_4	Methane
IPCC	Intergovernmental Panel on Climate Change
GWP	Global Warming Potential
USEPA	U.S. Environmental Protection Agency Estimation
EF	Emission Factor
SWC	Soil Water Content
PR/PE	Precipitation / Evapotranspiration
MM	Maize Monoculture
NH_4^+	Ammonium
NO_3^-	Nitrate
CT	Conventional Tillage
NT	No-Tillage
STICS	Simulateur Multidisciplinaire Pour Les Cultures Standards
DNDC	Denitrification and Decomposition
OMAFRA	Ontario Ministry Of Agriculture, Food And Rural Affaires
$FRAC_{Leach}$	Fraction Of Nitrogen Lost by Leaching and Runoff
NH_3	Ammonia
P_2O_5	Phosphate
HR	Herbicide-Resistant
a.i.	active ingredient

CHAPTER 1. INTRODUCTION

1.1. Background

The concentrations of key greenhouse gases in the atmosphere have changed dramatically since the Industrial Revolution. Furthermore, the climate change caused by increased carbon dioxide concentration will be largely irreversible for 1000 years after emissions stop (Solomon et al., 2009). The level of carbon dioxide (CO_2) in the atmosphere was 390.5 ppm in 2011, which was 40% greater than in 1750. Nitrous oxide (N_2O) was 324.2 ppb in the atmosphere in 2011 and has increased by 20% since 1750 (Hartmann et al., 2013).

It is believed that increased atmospheric greenhouse gas (GHG) due to anthropogenic emissions may lead to further severe climate change (Lal, 2004b). Extreme weather events and climate changes resulting from global warming are already signaling imbalances in Earth's natural systems (Pandey et al., 2011). The global mean surface temperature continues to increase and the first decade of the 21st century has been the hottest since the beginning of the instrumental record (Hartmann et al., 2013; Pérez et al., 2017). Shifting weather patterns and serious ecological imbalances can be caused by climate change (Muthu, 2006). Ice and snow cover is diminishing, sea levels are increasing, and extreme precipitation events are becoming more intense. On both short- and long-term scales, patterns of GHG emissions can have a major impact on climate change. It is crucial that we identify this pattern and develop suitable climate change mitigation strategies. The Intergovernmental Panel on Climate Change (IPCC) released a scathing report on global warming's progress, emphasizing the need for keeping temperature rises to 1.5°C rather than 2°C (IPCC, 2018). This goal requires large-scale adjustments in energy usage and consumption patterns, which may have a significant impact on agriculture's involvement in GHG mitigation and emissions. Agriculture accounts for 8% of total GHG (methane (CH_4) and nitrous oxide (N_2O)) emissions in Canada, making it the second largest emitter after energy (National Inventory Report, 2021).

Agriculture plays an important role in food security and sustainable development. Providing food for the world's people and other products for a variety of purposes. Plants use CO_2 from the atmosphere and nitrogen (N) from the soil in agricultural production, which are then distributed to living biomass, dead residues, and soil organic matter. In return, plant respiration, biomass

decomposition, and combustion emit CO_2 and other GHGs, such as CH_4 and N_2O, into the atmosphere. The agricultural sector is the largest source of anthropogenic non-CO_2 GHG in the world (Environmental Protection Agency; EPA, 2011). Annual GHG emissions from agricultural production from 2000 to 2010 were estimated to be 5.0–5.8 $GtCO_2$-eq/yr (Smith and Mercedes, 2015). Agricultural activities can alter GHG fluxes between land and the atmosphere, influencing climate change trends. However, according to global sectorial studies, forest protection has the potential to reduce emissions. Agriculture contributes the second largest share of mitigation potential, with 4.1 $GtCO_2$-eq yr^{-1} from improved rice cultivation and cropland soil carbon management (IPCC, 2022). Sustainable management of agriculture is a key component of climate change mitigation strategies. Although agriculture can be an emission source of GHGs, there are ways to reduce emission if improved management styles are identified and adopted (Hutchinson et al., 2007).

1.2. Challenges in the analysis of GHG emissions

In recent years, the concept of carbon footprint has gained increasing attention, arising from the broader concept of "ecological footprint". A carbon footprint is a measurement of the total amount of carbon dioxide emissions created by an activity, both directly and indirectly, or accumulated over the life stages of a product (Wiedmann and Minx, 2007).

This definition can be extended to include greenhouse gas other than CO_2, such as N_2O, which has 300 times the global warming potential of CO_2.Thus, carbon footprint is a quantitative expression of GHG emissions from an activity or sector. After the quantification of emissions, the most significant sources of emissions can be identified, and areas of emission reductions and increasing efficiencies can be prioritized (Pandey et al., 2011). For more effective climate change policies, carbon footprint analysis can be used to guide emissions control and mitigation measure evaluations (Matthews et al., 2008). Depending on crop characteristics and environmental conditions, whether a specific agricultural system is functioning as a sink or source of GHG emissions may change spatially. Hence, mitigation options for different regions may differ. The knowledge for spatially characterizing agricultural carbon footprints is currently inadequate, and it is necessary to fill this gap. It is also vital that effective methods to restrict the increase in global GHG concentrations are developed to avoid serious ecological and economic threats.

Carbon offsets are regarded as a way to account for both mitigation and adaptation. When emitters adapt an appropriate GHG reduction plan, they can get carbon credits. These credits can then be sold to people and businesses that want to offset their emissions. In previous efforts, by storing carbon on their land or reducing their GHG emissions, the Carbon Farming Initiative (CFI) in Australia allowed farmers and land managers to earn carbon credits. (Verschuuren, 2017). Alberta's Specified Gas Emitters Regulation (SGER) uses instruments such as the purchasing of offset credits, which can be passed between buyers and sellers through bilateral trading. This province has adopted a large number of highly diverse emission reduction protocols. In addition, there are 33 emission reduction activities that can generate offset credits (Tarnoczi, 2017). For instance, facilities that emit less than 100,000 tons of GHG in Alberta can obtain one offset credit for each ton of reduced emissions. Such offsets can be sold to large emitters that have not met their provincially mandated reduction targets (Kollmuss et al., 2010). British Columbia allows the use of carbon offsets to meet government greenhouse gas emission targets. There, afforested lands can be harvested, but still receive carbon offsets. The British Columbia afforestation protocol allows harvest by considering the permanence of the carbon that remains within the harvested wood product (Anderson et al., 2014). It is expected that an appropriate carbon offset system will help reduce GHG emissions while allowing emitters to make economically responsible choices (Kollmuss et al., 2010). To maximize the effectiveness of such efforts and support local programs and policies, offsets must be assessed with spatial accuracy. However, there are numerous barriers to designing offset programs and regulations that can maximize potential benefits while minimizing potential risks. There are still only a few estimation methodologies that explain how to implement an abatement project and measure the resulting reductions in GHG emissions. Scientists, government agencies, and industry bodies must develop methodologies for different implementable carbon-offset activities.

1.3. Objectives

To address the issues outlined in the previous section, this dissertation research will assess the GHG emissions of crop production in Ontario. For this research, an approach for the analysis of GHG emissions from crop production will be developed. Soybean will be used as the representative crop for the estimation of total GHG emissions. Ontario is the largest soybean producer in Canada, representing more than 50% of the country's total production, and offers a

suitable case study. The emissions will be quantified in different areas of Ontario, and the sensitivity of the model parameters will be further analyzed using factorial analysis. This research will have important implications for our efforts to mitigate climate change.

1.4. Organization

The dissertation is organized into six chapters, including an introduction, a literature review chapter, a methodology chapter, two results analysis chapters, and a concluding chapter. In Chapter 2, a literature review of previous agricultural GHG emission studies is provided. Chapter 3 introduces the methodology for analyzing crop GHG emission. In Chapter 4, the results of the assay of the GHG emissions of soybeans in Ontario are shown. In Chapter 5, the factorial-based sensitivity analyses of the results obtained in the previous chapter are explained. Finally, in Chapter 6, the conclusions of this dissertation are drawn.

CHAPTER 2. LITERATURE REVIEW

2.1. GHG emissions from agriculture

GHGs are the atmospheric gases that absorb infrared radiation, trapping heat and warming the Earth's surface; however, the ability to trap heat varies for each gas. CO_2, CH_4, and N_2O, which are associated with agriculture, are the three largest individual contributors to global warming (Snyder et al., 2009). Agriculture contributes significantly to anthropogenic global warming, and reducing agricultural emissions most notably CH_4 and N_2O may help mitigate climate change (Lynch et al., 2021). U.S. agriculture emitted 594.7 MMT CO_2-eq in 2020, accounting for 9.9% of the country's total GHG emissions (EPA, 2022).

According to the Intergovernmental Panel on Climate Change (IPCC), agricultural GHG emissions, which include crop and livestock production, forestry and associated land use changes, account for up to 30% of all anthropogenic emissions (Tubiello et al., 2013). Global atmospheric CO_2, CH_4, and N_2O concentrations have increased in recent decades as a result of human activities, including modern agriculture (Izrael et al., 2007).The increase in these greenhouse gases is seen by some groups as a fundamental cause of climate change. While fossil fuel use is the primary source of CO2, agriculture is a significant producer of CH_4 and N_2O emissions (Smith et al., 2007). CH_4 emissions, mainly from ruminant livestock (beef and dairy cattle) and rice cultivation contribute significantly to the global warming potential (GWP). Beef, which accounts for a much larger fraction of Canadian agricultural production than dairy production, is responsible for a significant portion of agriculturally sourced GHGs. Emissions from enteric fermentation and manure management account for 26.9% and 9.2% of the total CH_4 emissions from human activities, respectively. Beef and dairy cattle are the highest emitters of CH_4 among all domestic animals. Microbes living in an animal's digestive system ferment food consumed by the animal during digestive processes. In the enteric fermentation process, the microbes create CH_4 as a by-product, that must be breathed out or eructated by the animal. The amount of CH_4 generated and released by an individual animal is mostly determined by the digestive system of the animal and the amount and type of feed the animal consumes. Rice cultivation and agricultural residues from field burning are minor sources of methane. In 2020, U.S. total CH_4 emissions of livestock were 175.2 MMT CO_2-eq. Beef cattle continued to be the

major source of CH_4 emissions from enteric fermentation, accounting for 72% whereas emissions from dairy cattle accounted for 25% (EPA, 2022). In extremely anaerobic conditions, such as poorly drained localized areas, methane is generated in the soil due to decomposition of organic matter and CO_2 reduction (Gregorich et al., 2005).

N_2O emissions continue to increase, predominantly sourced from agriculture-nitrogen fertilizer use, manure application, the growth of nitrogen-fixing crops, and nitrogen deposition. Nitrogen deposition is linked to soil management, the application of nitrogenous fertilizer, and cropping practices (IPCC, 2022; Snyder et al., 2009). While, the most important human-related source of N_2O is agricultural soil management, it is also generated naturally in soil and water from a variety of biological sources (Kebreab et al., 2006). The nitrification and denitrification processes in soil produce N_2O and account for the majority of GHG emissions related to crop production in cold temperature regions (Gregorich et al., 2005).

Lime and urea applications, which generate CO_2, and crop residues burning which generates CH_4 and N_2O, are smaller sources of agricultural emissions. Agricultural land-use and land-use conversion activities, such as cultivation of cropland, grass land fires, grasslands management, and conversion of forest land to cropland are other agricultural activities that contribute to GHG emissions (EPA, 2022). Furthermore, GHG emissions can come from agricultural operations that are mostly related to energy, such as CO_2 emissions from stationary and mobile on-farm energy use or CH_4 and N_2O emissions from stationary on-farm energy use (EPA, 2022).

As a result, there is increasing urgency for the agricultural sector to develop techniques to reduce GHG emissions. Globally, agricultural soils contribute 60–80% of anthropogenic GHG emissions (Davidson, 2009). Soils are one of the most important sources of GHG emissions, contributing to anthropogenic emissions through land use changes and agricultural management (up to 22.5% of all anthropogenic sources) and natural terrestrial ecosystem emissions (Smith et al., 2008). Net CO_2 emissions from land use are estimated to account for roughly 14% of the annual anthropogenic CO_2, with agriculture directly accounting for 10%. (Mbow et al., 2019).

Agricultural CH_4 and N_2O were estimated to average 157 ± 47.1 Mt CH_4 yr^{-1}(4.2 ± 1.3 Gt CO_2-eq yr^{-1} and 6.6 ± 4.0 Mt N_2O yr^{-1}(1.8 ± 1.1 Gt CO_2-eq yr^{-1}) respectively, between 2010 and 2019 (IPCC, 2022). The annual GHG emissions from agricultural production from 2000-2010 were estimated to be 5.0-5.8 Gt CO_2-eq yr^{-1} (Smith and Mercedes, 2015) . In 2005, agriculture

was predicted to emit 5.1 to 6.1 Gt CO_2-eq yr^{-1}, accounting for 10–12% of total global anthropogenic emissions of GHGs; N_2O contributed 2.8 Gt CO_2-eq yr^{-1}, while CH_4 contributed 3.3 Gt CO_2-eq yr^{-1}. Agriculture accounted for about 60% of N_2O and about 50% of CH_4 of global anthropogenic emissions in 2005 (Smith and Cai, 2007). Furthermore, agricultural non-CO_2 emissions increased by 0.9 % per year between 1990 and 2010, with a slight rise in growth rates after 2005 (Tubiello et al., 2013).

Less than 10% of the total emissions of GHG from the United States were generated from agriculture, according to the U.S. Environmental Protection Agency's estimation (USEPA 2007). The agricultural sector in Canada produces approximately 10–15% of Canada's total GHG emissions (McRae et al., 2000). Total GHG emissions in Canada have been consistently rising ;747 Mt of CO_2 equivalent were emitted in 2007, with agriculture accounting for about 8% of total emissions (Beauchemin et al., 2011). According to the National Inventory Report (2021), emissions within the agriculture sector increased by 26% between 1990 and 2019. Rochette et al. (2018) listed the following variables as having an impact on N_2O emissions: growing season precipitation, ratio of growing season precipitation to potential evapotranspiration, mean annual air temperature, crop type (annual or perennial), soil pH, soil texture, and organic carbon content. According to their results, most agricultural areas contain enough nitrogen for denitrification, and the majority of N_2O is produced when the denitrifiers have enough anaerobic microsites. The use of nitrogen-based fertilizers is a main determinant of N_2O emissions, as excess nitrogen not utilized by plants is subject to emission, runoff, and leaching. Other soil management activities, such as tillage practices, irrigation, and drainage can affect N_2O fluxes, as well as fossil fuel CO_2 emissions and soil carbon (Beach et al., 2008). Besides, Perennial crops, in comparison to annual crops, likely affect N_2O emissions by increasing competition for available NO_3^-, reducing soil water, and decreasing the degree of anaerobiosis in the soils.

Of the gases emitted by agricultural activities, N inputs to crops and N_2O emissions from agricultural soils are the largest sources of GHGs (Desjardins and Riznek, 2000; Snyder et al., 2009). Annual N_2O emissions in Canada are predicted to be around 108 Gg N, of which agriculture accounts for about 76 Gg. Agricultural soils alone represent 55% of all agricultural N_2O emissions in Canada (Helgason et al., 2005).

Rochette et al. (2008) estimated the N_2O emissions from agricultural soils in Canada. To calculate the inventory of agricultural N_2O soil emissions, the authors developed a country-specific methodology. Regional fertilizer-induced emission factors (EFreg) were 0.0016 kg N_2O-N kg^{-1} N and 0.017 kg N_2O-N kg N^{-1} in the semi-arid brown and humid eastern provinces (Quebec and Ontario), respectively. In eastern Canada, fine-textured soil emissions were estimated to be 50% higher than coarse- and medium-textured soil emissions. Emissions throughout winter and spring thaw accounted for 40% of the GHG emissions of the snow-free seasons in eastern Canada. Gan et al. (2012b) reported that environmental conditions play an important role in the calculation of barley's carbon footprint. On average, barely grown in Indian Head had a carbon footprint of 0.281 kg CO_2-eq kg^{-1} of grain, which was significantly lower (11%) than barley grown in Swift Current (0.317 kg CO_2-eq kg^{-1} of grain). This was largely because barely grown at Indian Head had a significantly higher grain yield than the same crop produced in Swift Current. N fertilization the barley production accounted for more than 50% of total GHG emissions. Both grain yield and total GHG emissions were linked to barley's carbon footprint. Likewise, changes in the carbon footprint of canola production in the Canadian Prairies were studied by Shrestha et al. (2014). In the sub-humid zone of the Prairies, synthetic N fertilizer application accounted for 67% of total GHG emissions from the production of stubble-seeded canola (includes direct and indirect N_2O emissions as well as CO_2 emissions during the manufacture of N fertilizer), 11% were due to mineralized N from crop residues and 9% were due to farm operations. Comparable numbers were 50%, 19%, and 14% for fallow-seeded canola production, respectively. The authors found that lower amounts of applied the N fertilizer resulted in lower GHG emissions. Moreover, because of the wetter soil conditions, the sub-humid zone had consistently higher GHG emissions than the semi-arid zone.

Gan, et al. (2012) estimated the carbon footprint of three varieties of canola and two varieties of mustard grown in different parts of Saskatchewan. It was found that the carbon footprint was primarily determined by the rate of N fertilizer application. Nitrogen-related activities contributed 74% of total emissions produced during crop production. The carbon footprint of the oilseed's increased marginally when the rate of N fertilizer increased from 0 to 50 kg N ha^{-1} but when the rate of N fertilizer was more than 50 kg N ha^{-1}, large increases in carbon footprint occurred. The carbon footprint for the oilseeds production also varied with environmental circumstances and boundary selections.

2.2. GHG emissions from different cropping systems

Linquist et al. (2012) conducted an analysis of GHG emissions from the major cereal crop productions of rice, wheat, and maize, related GWP with grain yield. They found that the GWP of CH_4 and N_2O emissions from rice was much higher than that of wheat or maize. In rice, wheat, and maize, 0.68%, 1.21%, and 1.06% of N applied was emitted as N_2O, respectively. Choudhary et al., (2001) evaluated the impacts of continuous long-term tillage and seasonal changes in N_2O emissions where maize (*Zea mays* L.) was grown continuously in New Zealand temperate climate. They noted that in both pasture and cropped soils, soil water content (SWC) was a critical factor controlling N_2O emissions and when the gravimetric SWC content was less than 30%, lower emissions occurred. Throughout the summer (dry) season, the N_2O emissions from grazed pasture were low, but increased during the winter (wet) period.

The total GHG emission from the spring wheat cropping system in Saskatchewan was around 3.36×10^6 Mg CO_2-eq in 2012, with agricultural land being the major source of emissions (Shi et al., 2021). The total agricultural land emissions were roughly 1.55 Mg CO_2-eq, which accounted for 46.2% of total emissions from wheat fields. Citing evidence from their assessment, Shi et al. (2021) noted that the emission factor from direct emission had the most significant impact on overall GHG emission. Furthermore, total GHG emission was more sensitive to N fertilizer application in higher precipitation/evapotranspiration (Pr/PE) areas. Schwenke and Haigh (2016) investigated the interaction between N fertilizer rate and seasonal rainfall on total N losses, soil N_2O emissions and crop yields of sunflower and sorghum. They reported that applying N fertilizer at the time of sowing a summer crop resulted in N_2O emission and that the amount of N_2O lost depended on seasonal rainfall and N rate. Moreover, they noted that at all experimental sites, increased N fertilizer rates increased N_2O emission, although the rate of N loss was five times higher in wetter-than-average conditions than in drier seasons.

Ma et al. 2012 assessed the sustainability of the production of maize (*Zea mays* L.) grown either in a continuous culture or in rotation with a forage legume or soybean (*Glycine max* L. Merr) by calculating the total GHG emissions over 19 years. Compared to continuous maize monoculture (MM), maize following forage (alfalfa; FM) and grain (soybean; SM) legumes had lower carbon footprint. For 18 years of the 19-year period, maize treated with 100 kg N ha^{-1},

following soybean (SM) had a minimal impact on total GHG emissions (1%) but reduced the carbon footprint by 8%.

Wang et al. (2020) studied the carbon footprint of sugarcane/soybean intercropping. It was found that the carbon footprint values of the unit yield (CF_Y) for sugarcane/soybean intercropping were 3.2%–30.4% lower than those of the sugarcane monocropping systems, indicating that intercropping pattern has a higher carbon footprint efficiency. Sugarcane/soybean intercropping with decreased N input improved crop productivity while lowering the carbon footprint of sugarcane fields.

2.2.1. Major processes of nitrous oxide emission

Nitrification and denitrification are the main processes causing N_2O emissions in the soil. The aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) with N_2O as a by-product is known as nitrification. Under anaerobic conditions, NO_3^- is transformed to N_2O and then into inert N_2 in a two-step process known as denitrification.

The by-product of nitrification and denitrification is estimated to account for 65% of all N_2O emissions. Furthermore, the application of N fertilizers and animal manures are the main drivers of increases agricultural N_2O emissions to the atmosphere (Pete Smith and Mercedes, 2015). N_2O emissions are currently increasing at a rate of 0.25% each year, as agricultural activities intensify around the world (Wang et al., 2021). The GWP is an internationally acknowledged method for converting GHG into CO_2 equivalents established by the IPCC. The GWP of N_2O emissions was proven to be 298 times stronger than CO_2 in its contribution to global warming based on a 100-year GWP level (Huang et al., 2013). In terms of CO_2 equivalent, N_2O emissions account for 6% of annual worldwide GHG emissions (Ciais et al., 2013). When evaluating N_2O emissions from agricultural soils, it is critical to consider the factors that control N_2O emissions during nitrification and denitrification. Several articles have been published that define and classify the major elements influencing N_2O emissions from agricultural sites (Uchida and Akiyama, 2013). For example, Bouwman et al. (2002) identified factors affecting N_2O emissions and classified them into three categories: environmental, management, and measurement. These factors are valuable in understanding N_2O emissions and how they can be represented in simulation models. Cameron et al., (2013), Oertel et al., (2016), Signor and Cerri, (2013), and

Ghimire et al., (2020) studied factors affecting nitrification and denitrification processes, while Saggar et al., (2013) reviewed factors related to denitrification and N_2/N_2O ratios. The consideration of elements that influence N_2O emissions is important for N_2O modelling, since, in theory, adding as many of the impact factors as is feasible to a model will reduce the uncertainties associated with N_2O emission simulation (Wang et al., 2021).

2.2.2. Methods of GHG emission estimation

The net balance of carbon storage in soil is usually derived from long-term field experiments and/or simulation modeling, and measurements of GHG emissions from soil are done at small (e.g., soil chamber) or large scales (e.g., tower). Due to the significant temporal and spatial variabilities of GHG sinks and emissions, determining regional fluxes for accounting and reporting requires modelling and scaling up smaller-scale measurements conducted in fields or plots (Gregorich et al., 2005).

2.2.2.1. Field measurements

Researchers compared land uses and managements by taking in-situ measurements of soil organic carbon change and GHG from agricultural soils. According to Desjardins et al., (2020), Canadian scientists have devised a number of approaches for measuring agricultural GHG sources at various temporal and spatial scales. These techniques include the use of soil cores, and chambers that measure CO_2, CH_4, and N_2O uptake and release from soil. Soil cores are taken for many years to determine the amount and change of soil organic carbon (SOC) in agricultural soils. Because SOC is spatially variable, precise measurements incorporating many samples are required to provide an accurate estimate of SOC change. Thus, it is possible to assess the change in carbon overtime or between various land uses by using a representative average. As demonstrated by Desjardins et al. (2018), these methods can be used in conjunction with modeling to estimate emissions at the regional level. Gong et al. (2012) conducted a maize pot experiment, which included five treatments, to investigate SOC increases were driven by chemical fertilizer. They also determined carbon dioxide fluxes and microbial biomass carbon using a closed chamber. They found that fertilization increased SOC, maize biomass, SOC, and soil CO_2 emissions. In addition, it was concluded that the application of chemical fertilizer can increase crop-derived carbon and accelerate SOC decomposition.

Marland et al. (2003) studied changes in carbon sequestration and net GHG emission in agricultural soils following a conventional tillage (CT) to no-tillage (NT) conversion. They considered variations in CO_2 emissions caused by the consumption of fossil fuels, as well as the emissions of other GHGs. Their analysis supports the contention that a change from CT to NT agriculture will result in net GHG reduction, even if yields decrease somewhat and N_2O emissions from N fertilizer increase.

2.2.2.2. Models

Estimating greenhouse gas emission is a vital aspect of any quantitative research involving GHG and agriculture. Models can help us improve our understanding of farm operations and their interacting effects on GHG emissions. By providing a better understanding, they can help in the development and evaluation of mitigation strategies for decreasing emissions (Rotz, 2018). Both process and empirical models have been used to model GHG emissions and carbon change in Canada (Table 1) (Fouli et al., 2021). Over the last two decades, process models such as DayCent (Daily Century), DeNitificationDeComposition (DNDC), and Simulateur mulTIdisciplinaire pour les Cultures standards (STICS) have been used to simulate Canadian cropping systems, environmental effects, and their productivity (Guest et al., 2017). One of the main goals of these models is to estimate N_2O emissions from agricultural fields starting at local levels and working up to regional and national levels (Smith et al., 2013).

Table 1. Summary of strenghts and limitations of the current models used to estimate GHG emissions (Fouli et al., 2021)

Model	Strengths and Uses Scope, Capability, Intended Output	Limitations
Process Models		
DeNitificationDeComposition (DNDC)	The DNDC model focuses on nitrogen cycling and N_2O emissions, but also includes carbon change.	Testing and developing DNDC algorithms are an ongoing process that need regular updates assessments to accommodate for more farm practices. There is no documentation or version control. It is primarily used for scientific purposes.
Century	The century model was created to calculate carbon stocks and carbon change over the time scale of centuries.	Century has a long spin-up period and monthly time phases. It concentrates on carbon. Currently less in use and is mainly for scientific work.
DayCent	DayCent is daily time step version of the century model. It simulates soil carbon, nitrogen cycling and GHG emissions.	DayCents development appears to have been abandoned. Scientific purpose only.
Simulateur mulTIdisciplinaire pour les Cultures standards (STICS)	The STICS model focus on crop growth and nitrogen losses, recently incorporating N_2O losses. It incorporates various cropping practices. It is still being developed.	Long term changes are not taken into account by the STICS model. It is primarily for scientific use.
Empirical Models Holos Model	Holos calculates whole-farm emissions using National Inventory parameters and is designed for ease of use. It covers all livestock production and most crop types and systems. Upstream emission estimates are incorporated allowing this model to anticipate production system emission intensities and efficiencies.	The holos model in Canada specific. It is restricted to practices listed in the National Inventory.

Kristensen et al. (2011) applied a life cycle approach based on data from 35 farms to estimate the GHG emission at farm gate. Smith et al. (2010) developed an interface to integrate soil, climate and agricultural activity data in Canada; for this, they use the DNDC model to create a tool for estimating emission factors involved in agricultural management. DAYCENT (a process-based biogeochemical model) was used to estimate direct and indirect N_2O emissions from cropped land (Grant et al., 2016). Del Grosso et al.(2006) used a combined methodology from IPCC and DAYCENT to simulate crop soil N_2O emissions. Another tool worth mentioning is the Soil and Water Assessment Tool (SWAT), a process-based model that dynamically responds to environmental and management factors (Wang et al., 2021).

Holos, a tool for estimating and reducing greenhouse gases from farms, was created by Agriculture and Agri-Food Canada scientists in the Model Farm research program. It is a software program for whole-farm modeling that calculates GHG based on data from individual farms. The major goal of Holos is to test different approaches to reducing GHG emissions (Little et al., 2008). Moreover, using internationally recognized emission factors and easily accessible input parameters, this model can cover the vast majority of Canadian agriculture (Fouli et al., 2021).

2.2.3. N_2O emissions from agricultural soils

N_2O emissions from agricultural soils consist of both direct and indirect emissions. Direct channels include the soils where N is applied, and indirect channels, includes volatilization of inorganic N fertilizers, manure N as ammonia (NH_3), leaching and runoff nitrogen, result in N_2O emissions. The following approach is used to allocate nitrogen to a landscape: i) for each crop type, region-specific N application rates are calculated; ii) a recommended amount of nitrogen is allocated to each ecodistrict based on the application rate iii) the total amount of manure N available to be applied to agricultural soils is calculated based on the population of livestock (National Inventory Report, 2020).

2.2.4. Direct N_2O emissions from agricultural soils

Crop residues, organic N fertilizers, inorganic N fertilizers, mineralization associated with soil organic matter loss, and cultivation of organic soils are all direct sources of emissions from

agricultural soils. Soil N_2O emissions can also be influenced by tillage practices, irrigation and summer fallow (National Inventory Report, 2020).

Most direct emission sources are country-specific and incorporate the impact of moisture regimes, soil texture and landscape position on N_2O production rates (Rochette et al., 2008).

2.2.4.1. N_2O emissions during winter and spring thaw

In Eastern Canada, field measurements of N_2O flux using chambers are primarily performed during snow-free seasons. In the spring, snowmelt runoff generates wet soil conditions, which often stimulate N_2O production; furthermore, spring thaw emissions are influenced by the intensity of soil freezing during the winter (Wagner-riddle et al., 2007). Rochette et al. (2008) reported southern Ontario's mean N_2O emissions during winter and in the spring thaws to be 1.2 N_2O-N ha^{-1}.

2.2.5. Soil texture and N_2O emissions

Soil texture does not directly affect the production of N_2O in soils. However, it has a relationship with several chemical and physical characteristics that control N_2O production and transport in the soil profile. As a result, soil texture-related variables are linked to N_2O emissions from agricultural soils (Rochette et al., 2008).

2.3. Literature review summary

Since agriculture is a major source of GHG emissions, there is significant potential to help limit global warming by decreasing direct emissions from crop production, and indirect emissions from changes in land use. Some research efforts in the area of GHGs emission assessment have been undertaken in recent decades. However, many major issues surrounding GHG emissions from agricultural activities remain unresolved. We still do not have enough information to accurately model crop GHG emissions. For instance, the variations in crop GHG emissions at different scales are still unclear. Furthermore, estimating GHG emission is a complicated process with many variables to consider. Agricultural GHG emissions must assessed on various scales to support mitigation policies and facilitate GHG reduction efforts. To contribute to addressing these challenges, this study examines GHG emissions from the soybean

cropping system in Ontario, Canada. There have been few studies in Canada regarding GHG emissions from soybean cultivation and the studies do not include emissions from fertilizer production, farming operations, or herbicide usage to estimate total emission. The present study is the first assessment of GHG emissions from soybean fields in Ontario province with the aim of showing the roles and interactions of different factors related to this crop's production. Additionally, factorial analysis was used to investigate the sensitivity of the model's parameters.

It is predicted that integrated strategies and practices for maximizing agriculture's productivity while reducing GHG emissions in agricultural productions can be developed. Citizens are usually willing to pay for measures that minimize GHG emissions. Furthermore, some food companies are interested in displaying the CO_2 emissions generated during the production of particular food products. Thus, the accurate assessment of GHG emission can help create appropriate environmental policies, improve the agricultural management, and even generate greater interest in reducing GHG emissions.

CHAPTER 3. METHODOLOGY FOR THE ANALYSIS OF GHG EMISSION FROM SOYBEAN PRODUCTION

3.1. Emission sources

Emissions of CO_2, N_2O and CH_4 from agricultural practices can occur directly during agricultural activities such as planting and harvesting, or indirectly during the manufacturing and transport of required inputs such as herbicides, pesticides and fertilizers (Wood and Cowie, 2004).

GHGs can be derived from different sources during crop production (Figure 1). These include (1) emissions from the manufacturing and transportation of N and P fertilizer; (2) emissions from farming operations like tillage, seeding, chemical spraying, fertilizer application, and harvesting; (3) direct and indirect emissions from agricultural land; and (4) emissions from herbicide usage. The system boundary for GHG emissions from crop production is shown in Figure 2.
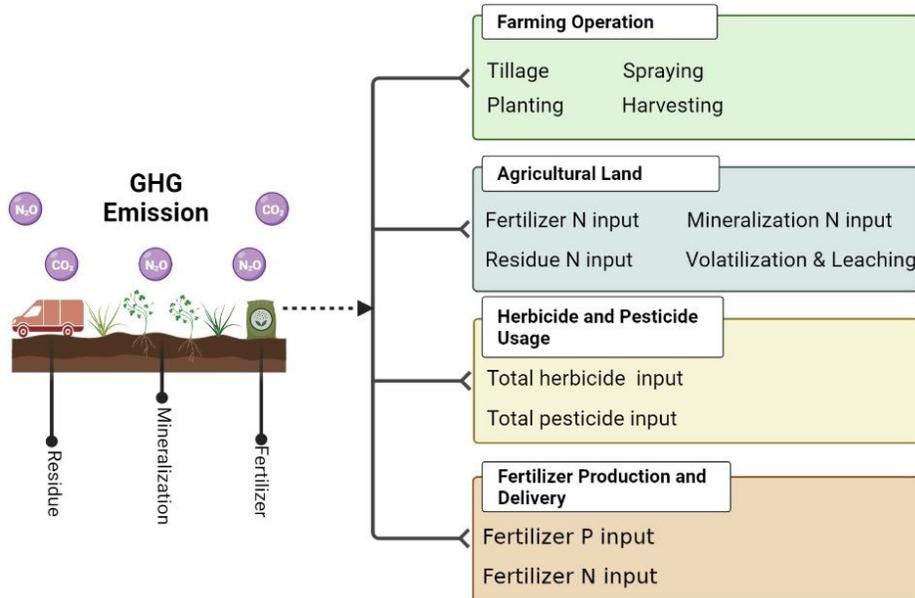
Figure 1. Sources of GHG in crop production process.
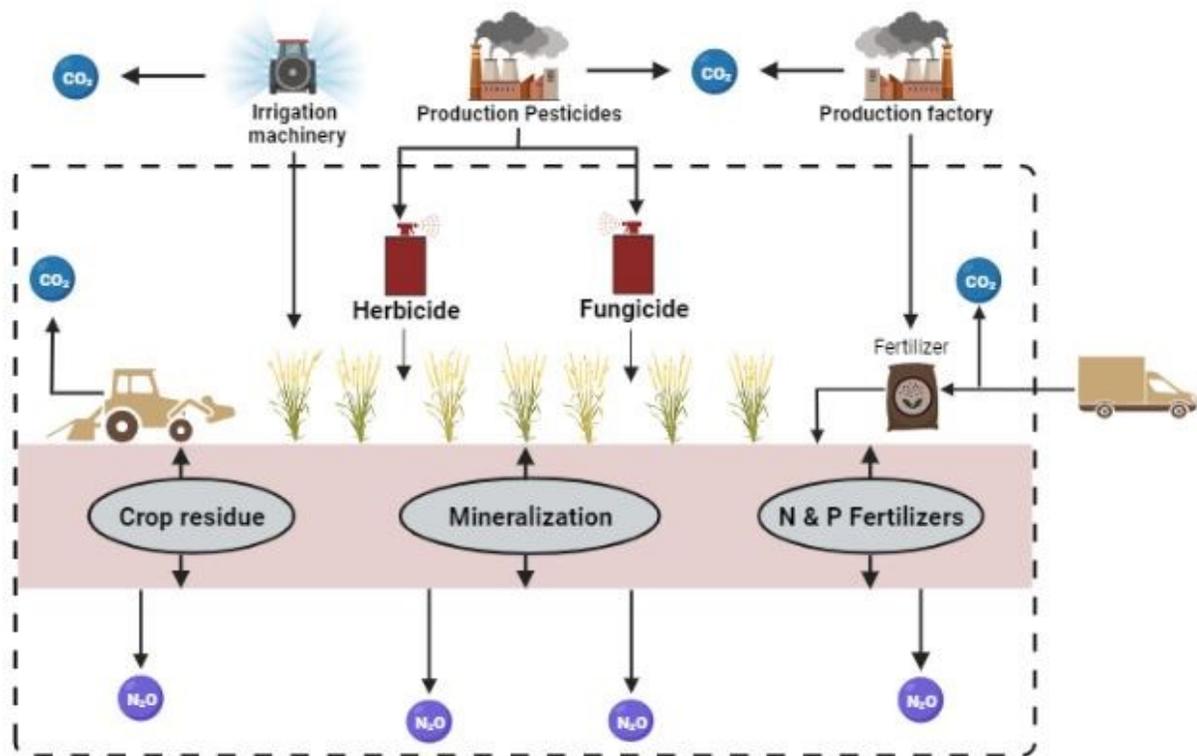
Figure 2. Boundary of GHG emission from crop production.

3.2. Emission from farming practices

Agricultural GHG emissions are intimately linked to farming practices, in which tillage and irrigation are two of the most significant sources (Lal, 2004b). Tillage operations mechanically disturb the soil in preparation for seeding. Fuel consumption during the tillage process can result in GHG emissions (Liu et al., 2013). Furthermore, conventional tillage management practices (moldboard plowing) can result in nutrient losses in soil. Moreover, this type of tillage can cause the degradation of soil structure, as well as higher GHG emissions (Chen et al., 2011). Meyer-Aurich et al. (2006) analyzed the economic efficiency of cropping options to mitigate net GHG emissions from agriculture in Eastern Canada. They found that conservation tillage reduced GHG emissions due to lower input use, but levels of sequestration did not differ significantly between tillage systems. According to West and Marland (2002) carbon emissions from agricultural machinery with moldboard plow operation averaged over corn, soybean, and wheat crops were 69.0, 42.2, and 23.3 kg C ha^{-1} yr^{-1} for conventional tillage, reduced tillage, and no-tillage, respectively. He et al. (2018) estimated the effects of climate change on crop yield and

N_2O emissions for conventional and no-tillage in Southwest Ontario, Canada. They found that the average yearly N_2O emissions for winter wheat increased by about 38.1% for conventional tillage and 17.3% for no-tillage, respectively. Emission from farming practices can be calculated as follows:

$$GHG_{farm} = K_{farm} \times A \qquad (3.1)$$

$$K_{farm} = K_{farm\text{-}till} + K_{farm\text{-}plan} + K_{farm\text{-}spra} + K_{farm\ harv} \qquad (3.2)$$

GHG_{farm}: GHG emission from farming practices, kg CO_2-eq yr^{-1}.
K_{farm}: GHG emission coefficient for farming practices, kg CO_2-eqha^{-1} yr^{-1}.
K_{farm_till}: GHG emission coefficient for farming practices about tillage, kg CO_2-eqha^{-1} yr^{-1}.
K_{farm_plan}: GHG emission coefficient for farming practices about planting, kg CO_2-eqha^{-1} yr^{-1}.
K_{farm_spray}: GHG emission coefficient for farming practices about spraying, kg CO_2-eqha^{-1} yr^{-1}.
K_{farm_harv}: GHG emission coefficient for farming practices about harvesting, kg CO_2-eqha^{-1} yr^{-1}.
A: the area of soybean, ha.

3.3. Emission from fertilizer production, transportation, storage, and delivery

The significant GHG emissions arising from the production of fertilizers are CO_2, N_2O and CH_4. In line with international greenhouse accounting practice, emission factors are expressed as carbon dioxide equivalents per unit mass of fertilizer product (e.g. g CO_2-eq kg^{-1} fertilizer) or element (e.g. g CO_2-eq kg^{-1} N) (Wood and Cowie, 2004).

The use of fertilizer is common due to its positive effect on plant growth. Applying different fertilizers results in greater soil fertility and crop productivity (Roba, 2018). Most soils are not sufficiently fertile for crop production, requiring periodic but regular treatments with macronutrients such as nitrogen (N), phosphorus (P) two of the four major nutrient inputs required for productive agriculture. The fertilizer industry mainly focuses on the supply of N and P (Mudahar and Hignett, 1987). Energy consumption for fertilizaer manufacturing, transport, and application all contribute to GHG emissions. The effect of nitrogen fertilizer application rates on N_2O emissions for potato production in Manitoba was examined by Gao et al (2013). They used different application rates to apply urea-N fertilizers to the soil. The cumulative N_2O emissions and yield-based N_2O intensity grew in a linear relationship with the rate of nitrogen application.

The results of their study showed that N_2O emissions can be reduced by avoiding fertilizer N applications beyond what is optimal for a marketable yield. Some main components, including N and Phosphate (P_2O_5), can be used to calculate the total emission. The total emission can be calculated using Equation (3.3).

$$GHG_{fert} = (E_{fert-N} \times N_{applied} + E_{fert-P} \times P_{applied}) \times A \tag{3.3}$$

GHG_{fert}: GHG emission from fertilizer production and delivery, kg CO_2-eq yr^{-1}.

E_{fert_N}: GHG emission rate caused by manufacturing, storage, and transportation of N fertilizer applied on farm, kg CO_2-eq kg^{-1} of N.

$N_{applied}$: N Fertilizer applied, kg N ha^{-1} yr^{-1}.

E_{fert_P}: GHG emission rate caused by manufacturing, storage, and transportation of P fertilizer applied on farm, kg CO_2-eq kg^{-1} P_2O_5.

$P_{applied}$: P Fertilizer applied, kg P_2O_5 ha^{-1} yr^{-1}.

3.4. Emission from herbicide and fungicide usage

The use of herbicides in crop production is increasing globally. Between 2002 and 2011, the value of the global herbicide market rose by 39%, and is expected to grow by another 11% by 2016 (Gianessi, 2013).There is increasing concern that herbicides, in addition to irradicating their target organisms (weeds), may affect the community of soil microorganisms and enzymatic activity in the soil, could consequently affect N_2O production (Jiang et al., 2015;Chen et al., 2009; Seghers et al., 2005). However, herbicides are not the only culprits that can affect GHG emissions. Planting soybean (Glycine Max) seeds and seedlings in cool and wet conditions exposes them to pathogens that may diminish plant populations, resulting in a lower yield. Thus, fungicides are used to protect against fungi and enhance seedling vigor (Pierson et al., 2018). According to previous studies conducted in North America and Ontario, Canada, soybean diseases reduce yield, grain quality, and seed quality in the United States and Canada every year. Many factors influence the occurrence of soybean disease that results in yield losses, including crop production practices, cultivar selection, environmental conditions, and past disease history (Mueller et al., 2016). According to the results from Bradley et al. (2017), total estimated losses due to soybean diseases (bushels in thousands) in Ontario from 2012 to 2014 were 10644, 10237,

and 16780, respectively, and the soybean cyst nematode was the most important disease. The average annual yield losses due to soybean diseases in the United States were estimated approximately 11%. Lal, (2004a) estimated carbon emission in kg carbon equivalent per kg of active ingredient (a.i.) of various pesticides were 5.1 for insecticides, 6.3 for herbicides, and 3.9 for fungicides. In addition, estimates of carbon emission range for production, transportation, storage and transfer of herbicides and fungicides was 1.7–12.6 and 1.2–8.0 kg carbon equivalent per kg active ingredients, respectively.

Petroleum products are used to make herbicides and fungicides. Both feedstock materials and energy consumption are related to GHG emissions in herbicide and fungicide production. The CO_2 emissions from the production of herbicides and fungicides were summarized by West and Marland (2002). It included the contributions from the produce of main active ingredients, the post-production process, and those from transportation and application. Moreover, GHG is emitted during pesticide manufacturing, packaging and transportation of herbicides, insecticides and fungicides from the factory to the farm (Ho, 2011). The GHG emissions contributions from herbicides and fungicides can be calculated as follows:

$$GHG_{herb} = E_{herb} \times A \qquad\qquad (3.4)$$

GHG_{herb}: GHG emission from herbicide usage, kg CO_2-eq yr^{-1}.
E_{herb}: GHG emission coefficient for herbicide usage, kg CO_2-eq ha^{-1} yr^{-1}.

$$GHG_{fung} = E_{fung} \times A \qquad\qquad (3.5)$$

GHG_{fung}: GHG emission from fungicide usage, kg CO_2-eq yr^{-1}.
E_{fung}: GHG emission coefficient for fungicide usage, kg CO_2-eqha^{-1} yr^{-1}.

3.5. Emission from agricultural land due to N input

Fertilizers cannot be completely used by crops after they have been applied to agricultural land. N, P, and K fertilizer recovery rates by crops can be as low as 50%, 25%, and 40%, respectively (Shi et al., 2021). Greenhouse gases can be derived from direct and indirect emissions from agricultural land.

When fertilizers are applied to agricultural soil, they undergo nitrification and denitrification, which results in the release of N_2O into the atmosphere. In addition, the agricultural residue

contains nitrogen, which decomposes to release nitrogen (Ho, 2011). The direct N_2O emissions from cop lands are primarily related to N inputs and can be affected by soil properties, climatic conditions, and farming operation modes. Total N inputs are usually calculated using N fertilizer, crop residue decomposition, and N mineralization (Beauchemin et al., 2010).

N_2O can be derived from N lost via volatilization, run-off and leaching. Some portion of nitrogen leaches from the soil, and some is volatilized when fertilizers are applied; these nitrogen losses can result in indirect N_2O emissions (Ho, 2011). The direct and indirect emissions from agricultural lands are shown in Figure 3.

3.5.1. Fertilizer N inputs

N fertilizer is a significant source of GHG emissions from land. For example, applications of synthetic N fertilizers for crop production generate N_2O. Furthermore,when fertilizer N inputs exceed a specific threshold, N_2O emissions may increase dramatically (Snyder et al., 2009). Over two growing seasons, Gao et al. (2013) examined the effects of N fertilizer application rates on N_2O emissions from irrigated potato production in clay loam soil in Manitoba. The treatments consisted of an unfertilized control, or urea-N fertilizer using different application rates. Following fertilizer application and rain or irrigation events, N_2O emissions peaked, with different responses between hills and furrows.The authors suggested that N_2O emissions can be reduced by minimizing fertilizer N application rates that are beyond what is needed for marketable yield, and limiting irrigation shortly after N fertilizer application. Malhi et al. (2006) observed the N_2O emissions when N input rates exceeded 80 kg ha^{-1}. In an irrigated corn study, similar results were also obtained when N input rates were greater than 100 kg ha^{-1} (Grant et al., 2006). The land GHG emissions due to fertilizer N inputs can be calculated as follows:

$$N_{fert} = N_{applied} \times A \tag{3.6}$$

N_{fert} : Fertilizer N input, kg N yr^{-1}

$N_{applied}$: N Fertilizer applied, kg N ha^{-1}yr^{-1}(4 kg N ha^{-1}yr^{-1})
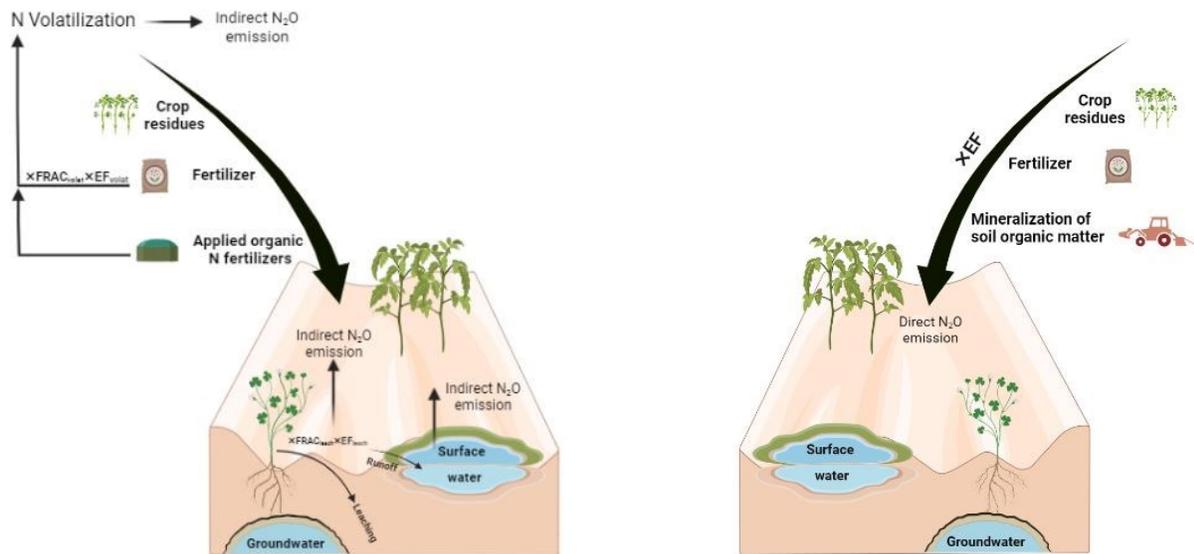
Figure 3. Indirect and direct emissions from agricultural land (FRAC$_{volat}$: Fraction of N lost by volatilization; EF$_{volat}$: Emission factor for volatilization; FRAC$_{leach}$: Fraction of N lost by leaching; EF$_{leach}$: Emission factor for leaching and runoff and EF: emission factor from direct emission).

3.5.2. Fertilizer P inputs

Beauchemin et al. (2010) assessed GHG emissions from beef production in western Canada. Their model considered all emissions from the manufacture of inputs (N and P fertilizers) and used 0.57 kg CO_2 as the emission factor in P fertilizer production. P fertilizer rates were 25, and 30 kg P_2O_5 ha^{-1} for barely grain, and barely silage, respectively. The Ontario Ministry of Agriculture, Food and Rural Affaires (OMAFRA) published the " Agronomy Guide for Field Crops," a technical resource for crop production. P_2O_5 guidelines for soybeans are based on OMAFRA–accredited soil tests that employ the sufficiency approach, appling the most cost-effective nutrient rate for a specific crop year. For example, if sodium bicarbonate phosphorus in the soil is 4–5ppm, the P required will be 60 kg/ha and if it is 13-15 ppm, 20kg/ha of phosphate will be required (Bagg et al., 2017). According to Cherian et al. (2016), soybean farms need high phosphorus and potassium, but low nitrogen; they get their N from the soil until they begin fixing it, at which point the fixed N becomes the main source of the nutrient. Phosphorous is

required for plant growth, nodule formation, and nitrogen fixing. This is especially important from pod formation to seed maturity.

$$P_{fert} = P_{applied} \times A \qquad (3.7)$$

P_{fert}: Fertilizer P input, kg N yr^{-1}

$P_{applied}$: P Fertilizer applied, kg N ha^{-1}yr^{-1}(18 kg N ha^{-1}yr^{-1})

3.5.3. Crop residue N input

The direct N_2O emissions from soils are based on N inputs, and crop residue decomposition (above- and below-ground residue) is one of the contributors to the total N inputs. Crop residues provide several advantages when left on land, including increased carbon sequestration, erosion protection, improved soil aggregate stability, and enhanced water holding capacity. However, their decomposition beneath the soil can result in the release of GHGs. After harvest, nitrogen in crop residue supplied an additional source of nitrogen for the nitrification and denitrification, resulting in N_2O emissions. Frimpong and Baggs (2010) pointed out that crop residues may play a variety of roles in mediating N_2O emissions in soil. As organic N fertilizers, they are subject to microbial N mineralization and nitrification, resulting in N_2O generation. Crop residue production has reached 4 billion metric tons per year globally and around 1.5 billion metric tons annually in the United States. Soil carbon sequestration may benefit from the retention of this significant volume of residue on agricultural land. However, such potential effects could be offset if residue retention significantly increases soil emissions of N_2O, a potent greenhouse gas and ozone-depleting chemical (Chen et al., 2013).

Beauchemin et al. (2010) used Holos to conduct a life cycle assessment to estimate whole-farm GHG emissions from beef production in western Canada. They listed different crop factors used in beef emission life cycle analysis and reported 0.007, 0.015, 0.01, and 0.015 kg N kg^{-1} above and below ground residue N concentrations for barley grain and mixed hay, respectively. The quantity of nitrogen in crop residue (N_{res}) can be obtained based on the aboveground and belowground crop residue biomass and corresponding N concentrations:

1. Above-ground residue

$$AGresi\_yield = [Yield - (Moisture\_content \times Yield)] \times \frac{AGresi\_ratio}{Yield\_ratio} \qquad (3.8)$$

AGresi_yield: Aboveground residue yield, kg residue ha^{-1} yr^{-1}.

Yield: Crop yield, kg crop ha^{-1} yr^{-1}.

Moisture_content: Moisture content of crop yield (w/w).

AGresi_ratio: Ratio of aboveground residue.

Yield_ratio: Ratio of yield.

$$AGresi\_N = AGresi\_yield \times AGresi\_N\_conc \qquad (3.9)$$

$$= [Yield - (Moisture\_content \times Yield)] \times \frac{AGresi\_ratio}{Yield\_ratio} \times AGresi\_N\_conc$$

AG_{resi_N}: Aboveground residue N, kg N ha^{-1} yr^{-1}.

$AG_{resi\_N\_conc}$: Aboveground residue N concentration, kg N kg^{-1} residue.

2. Below-ground residue

$$BGresi\_yield = [Yield - (Moisture\_content \times Yield)] \times \frac{BGresi\_ratio}{Yield\_ratio} \qquad (3.10)$$

BGresi_yield: Belowground residue yield, kg residue ha^{-1} yr^{-1}.

BGresi_ratio: Ratio of belowground residue.

$$BGresi\_N = BGresi\_yield \times BGresi\_N\_conc \qquad (3.11)$$

$$= [Yield - (Moisture\_content \times Yield)] \times \frac{BGresi\_ratio}{Yield\_ratio} \times BGresi\_N\_conc$$

BG_{resi_N}: Belowground residue N, kg N ha^{-1} yr^{-1}.

$BG_{resi\_N\_conc}$: Belowground residue N concentration, kg N kg^{-1} residue.

3. Total N inputs from crop residue returned to soil

$$N_{resi} = (AGresi\_N + BGresi\_N) \times A \qquad (3.12)$$

$$= (1 - moisture\_content) \times Yield \times \left(\frac{AGresi\_ratio}{Yield\_ratio} \times AGresi\_N\_conc + \frac{BGresi\_ratio}{Yield\_ratio} \times BGresi\_N\_conc \right) \times A$$

N_{resi}: N inputs from crop residue returned to soil, kg N yr^{-1}.

3.5.4. Mineralization N inputs

Total N input is comprised of inputs from crop residue decomposition (above-ground and below-ground residues), synthetic N fertilizer, and net N mineralization (estimated from net change in soil carbon). Soil N availability is a major determinant of the microbial processes that produce N_2O in agricultural soil. It is influenced by mineralization and immobilization processes that occur when soil organic matter stocks are altered by management techniques or land use modifications. Changes in management frequently result in rapid soil carbon losses and nutrient flushes, including nitrogen. The magnitude of soil carbon loss, the C:N ratio of soil organic matter, and the location of the change in land use or management practices all influence net mineralized soil N (N_{min}) (Rochette and McGinn, 2008). Soil carbon loss causes N mineralization and, as a result, creates N_2O emissions. Nitrogen inputs from N mineralization are a function of soil carbon (IPCC, 2006).

$$N_{mine} = C_{mine} \times \frac{1}{CN\_Ratio} \tag{3.13}$$

N_{mine}: N inputs from mineralization of native soil organic matter, kg N yr^{-1}. This value can only be positive. If the result is negative, then $N_{mineral}$ is equal to 0.

C_{mine}: C change, kg C yr^{-1}.

CN_Ratio: C:N ratio of soil organic matter.

Soil carbon can be altered by changes in land management methods. The carbon change due to the change in tillage practice is calculated as (McConkey et al., 2014):

$$\Delta C_{till} = LumC_{max\_till} \times (e^{[-K_{till} \times (Y_{till}-1)]} - e^{[-K_{till} \times Y_{till}]}) \tag{3.14}$$

ΔC_{till}: C change rate due to change in tillage practice, g m^{-2} yr^{-1}.

$LumC_{max\_till}$: Maximum C produced by management change in tillage practice, g m^{-2}.

e: Exponential function

K_{till}: Rate constant for the change in tillage practice, yr^{-1}.

Y_{till}: Time since management change of tillage, yr.

$$C_{mine} = C_{till} = \Delta C_{till} \times 10 \times A_{till} \tag{3.15}$$

C_{till}: C change for annual crop area due to change in tillage practice, kg C yr⁻¹.

A_{till}: Area of management change in tillage practice, ha.

10: conversion from g m⁻² yr⁻¹ to kg ha⁻¹ yr⁻¹.

3.5.5. Direct emissions

Direct N_2O emissions from agricultural soils were calculated as a fraction of soil N inputs using the method provided by (IPCC, 2006). Direct emissions were estimated as follow: 44/28 is the conversion coefficient from N_2O–N to N_2O, and 298 is the GWP of N_2O for the 100-year period (IPCC, 2006).

$$GHG_{N\_input\_direct} = \left(N_{fert} + N_{resi} + N_{mine}\right) \times EF_{direct} \times \frac{44}{28} \times 298 \qquad (3.16)$$

$GHG_{N\_input\_direct}$: GHG emission due to direct emission from N input, kg CO_2-eq yr⁻¹.

EF_{direct}: Emission factor from direct emission, kg N_2O-N kg⁻¹ N.

44/28: Conversion from N_2O-N to N_2O.

298: global warming potential of N_2O, kg CO_2-eq kg⁻¹ N_2O.

Direct N_2O emission factors were estimated based on the ratio of growing season precipitation to evapotranspiration (Rochette et al., 2008).

$$EF_{direct} = \frac{0.022 Pr}{PE} - 0.0048 \qquad (3.17)$$

The Blaney-Criddle method was used to calculate evapotranspiration. The following equation describes the relationship between the reference grass crop and the crop that was actually grown:

$$PE = K_c \times PE_o \qquad (3.18)$$

where K_c is the crop factor and PE_0 is the reference evapotranspiration (mm/day). The reference crop evapotranspiration (mm/day) as an average for a period of one month can be calculated as follows:

$$PE_o = DT_{perc} \times (0.46 \times T_{mean} + 8) \qquad (3.19)$$

where T_{mean} is the mean daily temperature (°C) and DT_{perc} is the mean daily percentage of annual daytime hours (Armanuos et al., 2016).

3.5.6. Indirect emissions

3.5.6.1. GHG emissions due to leaching and runoff

When fertilizer and crop residue are applied to cropland, a portion of the nitrogen is lost via leaching and run off. The size of this loss depends on certain parameters, including application method and rate, soil texture, crop type, and rainfall. This nitrogen can undergo transformations, such as nitrification and denitrification, and can produce N_2O emissions (National Inventory Report, 2021). In regions where only a single main crop is grown, such as Canada cover crops avoid bare soil periods, which are linked to increased nitrogen leaching losses (Abdalla et al., 2019). Cover crops are plants that are grown after the primary crop has been harvested.

Nitrogen leaching from agricultural soils is of great concern due to its contribution to excess NO3- concentrations in run–off, indirect emissions of GHGs such as N_2O, and losses of N fertilizer (Ascott et al., 2017). The fraction of nitrogen lost by leaching and runoff ($FRAC_{leach}$) is multiplied by the amount of N fertilizer, crop residue N, and N mineralization (N_{min}). An emission factor of 0.0075 kg N_2O-N kg^{-1} N is used to estimate indirect N_2O emissions from runoff and leaching of nitrogen at the ecodistrict level (IPCC, 2006). The $FRAC_{leach}$ was calculated as (Rochette et al., 2008):

$$FRAC_{leach} = \frac{0.3247 Pr}{PE} - 0.0247 \qquad (3.20)$$

$FRAC_{leach}$: Fraction of N lost by leaching.

Pr: Growing season precipitation (May-October), cm/month.

PE: Growing season potential evapotranspiration (May-October), cm/month.

$$N_{leach-N_2O} = Total\_N_{input} \times FRAC_{leach} \times EF_{leach} \qquad (3.21)$$

$N_{leach-N2O}$: N emissions due to leaching, kg N_2O-N yr^{-1}.

$Total\_N_{input}$: Total N inputs, kg N yr^{-1}.

EF_{leach}: Emission factor for leaching and runoff. 0.0075 kg N_2O-N kg^{-1} N(IPCC, 2006).

$$GHG_{leach} = (N_{fert} + N_{resi} + N_{mine}) \times FRAC_{leach} \times EF_{leach} \times \frac{44}{28} \times 298 \qquad (3.22)$$

GHG_{leach}: GHG emission due to leaching, kg CO_2-eq yr^{-1}.

3.5.6.2. GHG emissions due to volatilization

Ammonia (NH_3) volatilization is a major source of nitrogen loss in agricultural systems around the world, and is conducive to low fertilizer N use efficiency, environmental issues, and indirect N_2O emissions. Pan et al. (2016) conducted a meta-analysis of 824 observations of the effects on NH_3 volatilization. They reported that up to 64% (an average of 18%) of the applied nitrogen was lost as NH_3. Moreover, the volatilization of NH_3 significantly increased with the residue retention and N application rates. Their findings confirmed that NH_3 volatilization causes a significant loss of nitrogen from agricultural systems. According to Bouwman et al.'s (2002b) average value (14%) for volatilization, 11.2–15.7 million tons of fertilizer-N are lost as NH_3-N globally.

A proportion of N can be volatilized as NH_3, resulting in GHG emissions. Fertilizers, surface residues, and crop canopies all contribute to GHG emissions due to volatilization (Shi et al., 2021). This portion of GHG emissions can be calculated as follows:

$$N_{volat\_N_2O} = N_{fert} \times FRAC_{volat} \times EF_{volat} \qquad (3.23)$$

N_{volat_N2O}: N emissions due to volatilization, kg N_2O-N yr^{-1}.

$FRAC_{volat}$: Fraction of N lost by volatilization.

$FRAC_{volat}$ = 0.1 (IPCC, 2006)

EF_{volat}: Emission factor for volatilization, kg N_2O-N kg^{-1} N.

EF_{volat}=0.01 kg N_2O-N kg^{-1} N (IPCC, 2006)

$$GHG_{volat} = N_{fert} \times FRAC_{volat} \times EF_{volat} \times \frac{44}{28} \times 298 \qquad (3.24)$$

GHG_{volat}: GHG emission due to volatilization, kg CO_2-eq yr^{-1}.

3.5.7. Total GHG emission from agricultural land

$$GHG_{N\_input} = GHG_{N\_input\_direct} + GHG_{leach} + GHG_{volat}$$

3.6. Total GHG emissions

The total GHG emission from spring wheat production is calculated as

$$\sum_{i=1}^{m}\sum_{j=1}^{n} GHGtotal, ij$$

$$= GHG_{farm,ij} + GHG_{fert,ij} + GHG_{pest,ij} + GHG_{herb,ij} + GHG_{Ninput,ij}$$

where i is the crop district and j is the copping year.

CHAPTER 4. GHG EMISSION FROM THE PRODUCTION OF SOYBEANS IN ONTARIO

4.1. Study area

4.1.1. Environmental conditions of Ontario

Ontario is one of the central provinces of Canada, and is the country's second-largest province by total area (Figure 4). It has a total area of 1,076,395 km^2, including a land area of 917,741 km^2 and the rest of the area is water. Ontario can be sometimes conceptually divided into five regions: northern, southern, eastern, western, and central Ontario. The province is bordered in the west by Manitoba, in the north by Hudson Bay, in the east by Quebec, and in the south by the United States. The climate in Ontario varies by season and location. It is influenced by three air sources: cold, dry arctic air from the north, Pacific polar air crossing in from the western Canadian Prairies, and warm, moist air from the Gulf of Mexico. The impact of these air masses on precipitation and temperature depends on latitude and proximity to water. In general, most of Ontario's climate is classified as humid continental. The Canadian soil classification system is a set of orders and component great groupings that can be used to identify and classify soils. In Ontario, six soil orders form this classification are the most common. These are the organic and related organic cryosolic soils in the northern parts of the province, brunisols in the northwest part of the Shield and south of the Canadian Shield, podzols over much of the central and southern parts of the Shield, luvisols in southern Ontario, gleysols in poorly drained areas, and regosolic soils that are dominant only in a thin band along the southwest shore of Hudson Bay (Baldwin et al., 2000).

4.1.2. Soybean production in Ontario

The province of Ontario accounts for 25.6% of Canada's agriculture operations and generates 20% of the country's overall farm receipts. In Ontario, there are 50,000 farms covering 5 million ha. This province produces the most corn and soybeans, which account for almost 50% and 60% of its total farmed area, respectively. Ontario continues to be reported as the country's greatest area for soybeans and corn for grain (Table 2). In 2016, the province's croplands accounted for 49.6% of the national soybean area, and this crop's acreage in Ontario has grown since the last

census (Statistics Canada, 2017). In 2019, total soybean production from Ontario was 136,251,400 bushels, or 3,708,200 metric tons. In 2021, Ontario was the largest contributor of Canada's soybean production. with 65% of total production and average yields of 43.7 bushels per acre (Figure 5). The soybean fields in Ontario are mainly in the south and west regions of the province. As previously mentioned, the province is divided into five agricultural regions, each comprised of different crop districts (Figure 6 and 7)

Due to data availability, the GHG emissions of soybean crops for each region in Ontario were evaluated based on 2018 data. The seeding area and soybean production per unit area by crop region in 2018 are shown in Figures 8 and 9, respectively. Southern and western Ontario had the largest seeding areas, and northern Ontario had the lowest soybean production per unit area.

Table 2. Largest three field crops, Ontario, 2011 and 2016 (Statistics Canada, 2017).

Field crop	Acreage 2011	Acreage 2016
Soybean	2464870	2783443
Corn for grain	2032356	2162004
Winter wheat	1100003	1080378
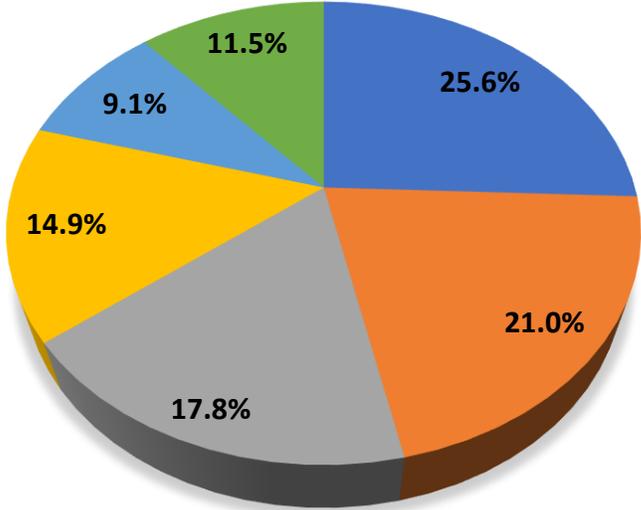
Figure 4. Provincial distribution of agriculture operations, 2016 (Statistics Canada, 2017).
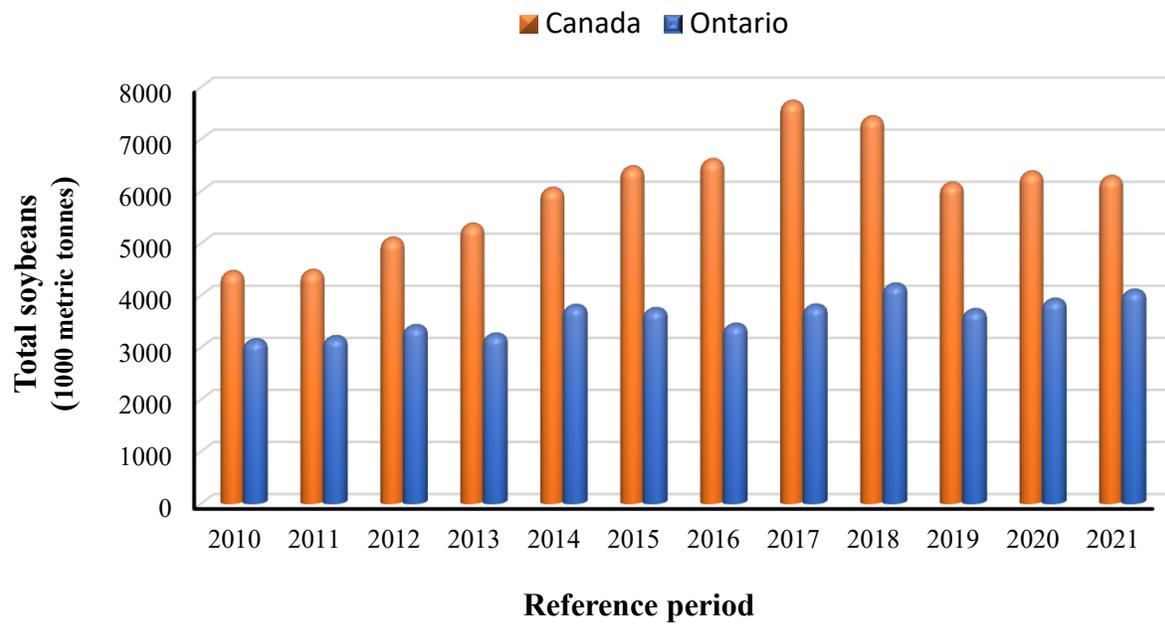
Figure 5. Soybean production yields of Canada and Ontario (Statistics Canada, 2022).

Figure 6. Ontario agricultural regions (Statistics Canada, 2017).

(A) Subdivisions 3 and 4

(B) Subdivisions 5
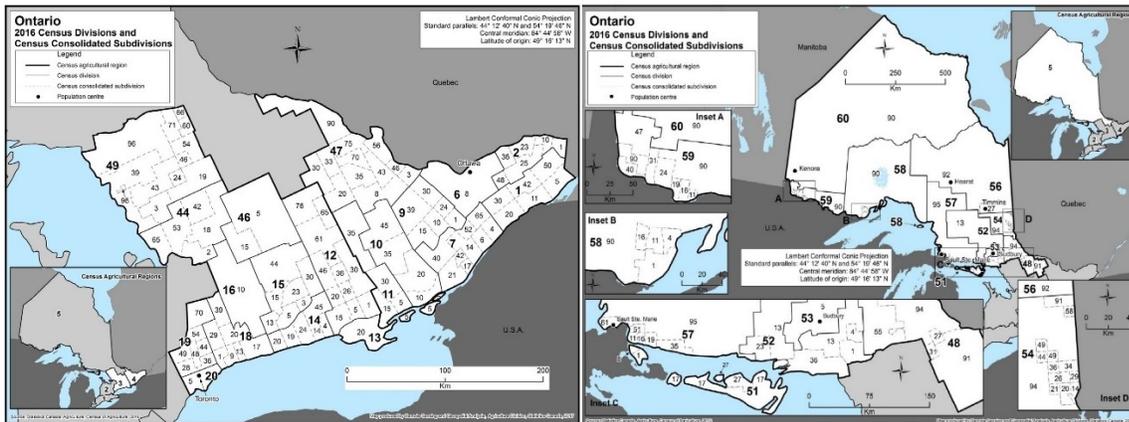
(C) Subdivisions 1 and 2
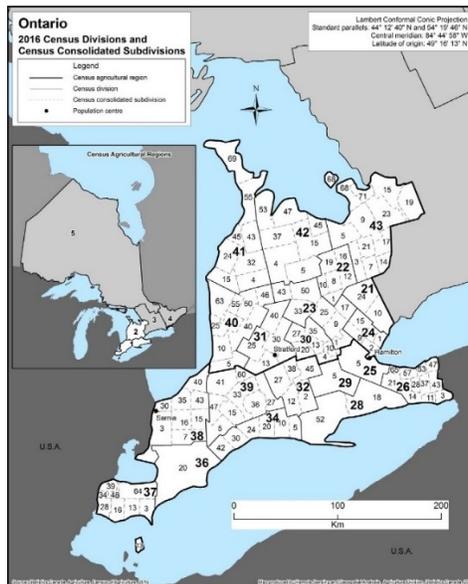
Figure 7. 2016 census divisions and census consolidated subdivisions (A) Central and Eastern Ontario (B) Northern Ontario (C) Southern and Western Ontario (Statistics Canada, 2017).
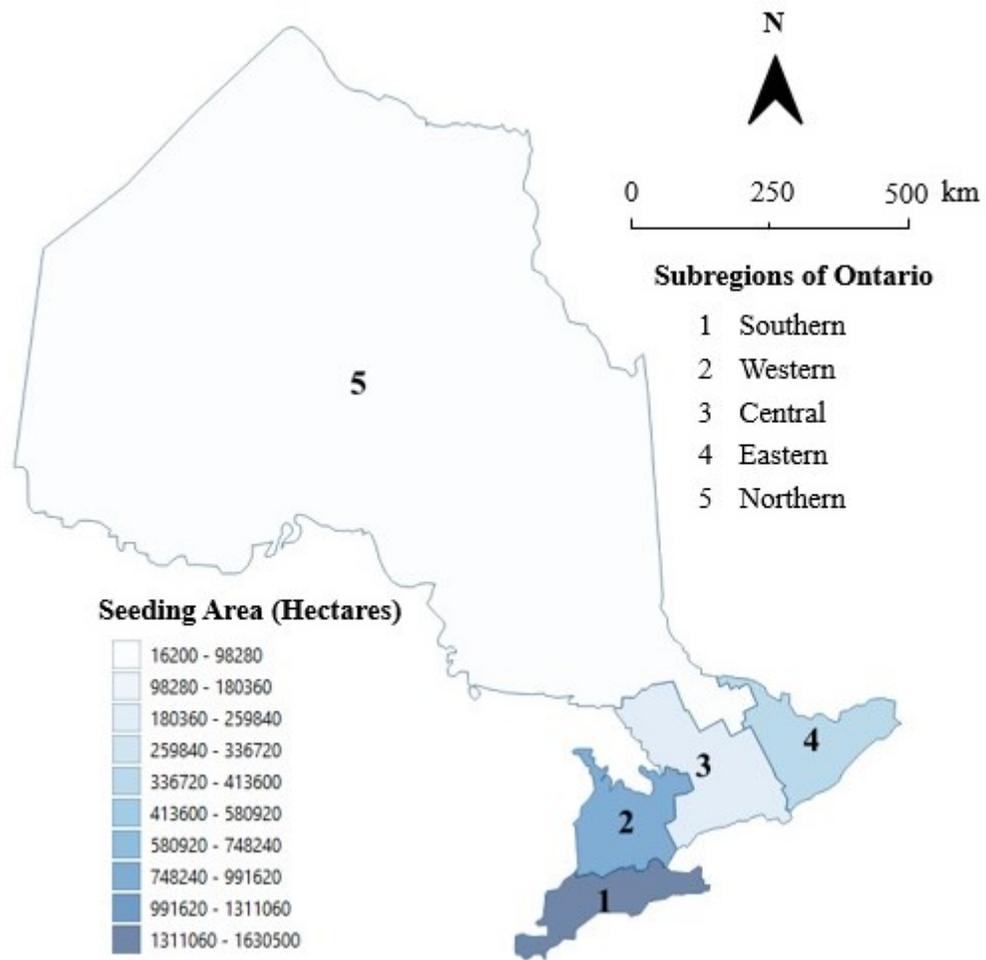
Figure 8. Soybean seeding area
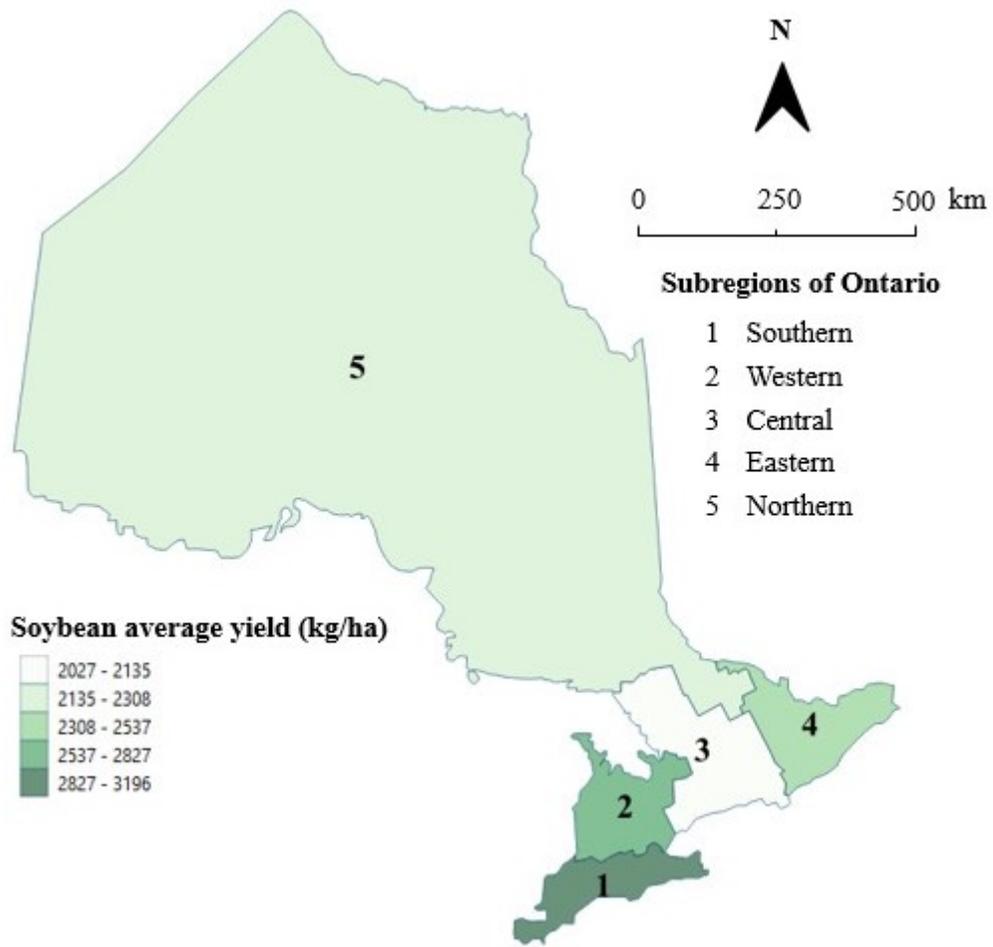
Figure 9. Average crop district soybean production.

4.2. GHG emission from farming practice

Farming has significant environmental consequences, as most farm inputs are substantial sources of GHG (Goglio et al., 2014; Yue et al., 2017). For instance, the unbalanced uses of pesticides and inorganic fertilizers in high-yielding farming systems contribute to GHG emissions (Wang et al., 2017).Various farming operations, such as sowing, spraying, and harvesting crops produce GHG emissions. Meyer-Aurich et al. (2006) evaluated tillage options for reducing net GHG emissions from agriculture. Using data from a 20-year field experiment in Ontario, they demonstrated that conservation tillage reduces GHG emissions due to lower input use. They also pointed out that conservation tillage decreases N_2O emissions and produces less crop residue due to reduced crop yields. Reduced tillage may result in less soil erosion, more soil moisture conservation, and enhanced soil structure (Baan et al., 2009). From 35 comparisons in western Canada, VandenBygaart et al. (2003) found that reduced tillage increases carbon sequestration. Agricultural operations that used no-tillage produced less CO_2 than those that applied conventional tillage (West and Marland, 2002). Thus, it is possible to reduce CO_2 emissions by switching from conventional tillage to no-tillage pattern. Furthermore, no-tillage systems can affect soil carbon sequestration and N_2O emissions (Gregorich et al., 2008). Reduced tillage and no-tillage farming are the major patterns of soybean production in Ontario ("Census of Agriculture," 2016). For this study, it was assumed that the croplands were no-tillage ecosystems in the emission calculation for 2018. The emission coefficients for tillage, planting, herbicide and fungicide spraying, and harvesting were estimated to be 14, 14, 5, and 37 kg CO_{2-eq} ha^{-1} yr^{-1}, respectively (Lal, 2004b). The total emissions coefficients associated with various farming operations were around 70 kg CO_{2-eq} ha^{-1} yr^{-1}.

$$GHG_{farm} = K_{farm} \times A = K_{farm-till} + K_{farm-plan} + K_{farm-spray} + K_{farm-harv}) \times A \tag{4.1}$$

$$= (14+14+5+37) \times A = 70 \text{ kg } CO_{2-eq} \text{ ha}^{-1} \text{ yr}^{-1} \times A$$

4.3. GHG emission from fertilizer production, transportation, storage, and delivery

Based on emission variables and the amounts of fertilizer applied in the seeding area, GHG emissions from the production, transportation, storage, and distribution of fertilizers for crops were calculated (Gan et al., 2012c). Previous studies in North America estimated the emission

factors for N and P fertilizers to be 4.8 kg CO_2-eq kg^{-1} of N and 0.73 kg CO_2-eq kg^{-1} of P_2O_5 fertilizers, respectively (Gan et al., 2011a). These emission factors were multiplied by the amount of N and P fertilizers on a per-hectare basis to calculate emissions from fertilizer production, transportation, and delivery to farm fields. Soybean fields require low nitrogen but high phosphorous and potassium. Soybeans get their nitrogen from the soil until fixation begins, at which point the fixed nitrogen becomes the main source of the nutrients. As recommended by the Ontario Ministry of Agriculture, the N application rate should be 4 kg N ha^{-1} within the top 60 cm of soil for soybean (Cherian et al., 2016). Excess nitrogen can cause nodule formation and nitrogen fixation to be delayed and promote excessive vegetative growth which increases the risk of lodging. If nodulation does not occur and the soybeans are pale green and N deficient, the recommended remedy is to apply 25 kg N ha^{-1} as urea or calcium ammonium nitrate at first flower (Bagg et al., 2017). Plant development, nodule formation, and nitrogen fixing all require phosphorus. This nutrient is especially important from pod formation to seed maturity. In soybeans, P should either be applied as a banded application to meet crop needs, or P needs should be addressed throughout the rest of the crop rotation (Cherian et al., 2016). In Ontario, it is recommended that P fertilizer be applied at a rate of 18 kg P_2O_5 ha^{-1}.

$$GHGs_{fert} = E_{Nfert} \times N_{applied} \times Area + E_{Pfert} \times P_{applied} \times Area \qquad (4.2)$$

$$= 4.8 \times 4 \times Area + 0.73 \times 18 \times Area = 32.34 \times Area$$

4.4. GHG emission from herbicide and fungicide usage

Several soilborne plant diseases, such as *Fusarium*, *phytophthora*, *Pythium*, and *Rhizoctonia*, negatively influence the population of soybeans. Fungicide applications in soybeans are typically seed applied or foliar applied at beginning pod (R3). Fungicides, such as Priaxor, Acapela, and Cotegra, are often used for soybean production in Ontario (OMAFRA, 2021). Over the past decade, a variety of herbicide-resistant (HR) crops have been registered in eastern Canada; glyphosate-resistant, glyfosinate-resistant, and sulfonylurea-resistant soybean (*Glycine max*) were among them. Glyphosate has a wide window of application in glyphosate-resistant soybeans, and it is significantly more flexible than some conventional herbicides, such as fomesafen, which is only registered for soybeans from the first to second trifoliate (Gulden, Robert H.; Swanton, 2018). Common waterhemp is one the most important weeds of soybean

fields in Ontario, as its interference results in soybean yield losses. Various pre-emergence herbicides such as metolachlor and dimethenamid, and post-emergence herbicides, such as fomesafen, are used to control waterhemp in soybean crops (Vyn et al., 2007). GHG emissions associated with herbicides and fungicides arise from their production, transportation, storage, and field application. The average emission factors for herbicides and fungicides were reported to be 23.1 and 14.3 kg CO_2-eq ha^{-1}, respectively (Lal, 2004a). The timing of insects and diseases that can cause damage and yield loss in soybean fields is variable. For example, downy mildew often occurs in August and September, while soybean cyst nematodes have an adverse effect on soybean fields from June to mid-October (Bagg et al., 2017).

The herbicide resistance pattern, weed density, and environmental conditions all play important roles in successful weed control in soybean fields. A single pre-emergence or post-emergence herbicide application may be sufficient for full-season management in some environments. In other environments, weed control professionals must be prepared to use a sequential approach to achieve acceptable control. For instance, in conventional soybean, a pre-emergence herbicide followed by a post-emergence in-crop application may be used to control late-emerging waterhemp (Vyn et al., 2007). In this study, it was assumed that there was no fungicide usage during soybean production.

4.5. GHG emission from agricultural land

4.5.1. Fertilizer N inputs

Soybean, which is one of the most important crops in Ontario, has a symbiotic N_2-fixing association with *Bradyrhizobium japonicum*. The main sources of supplying the N demand of high-yielding soybeans are biological N_2 fixation, mineral soil, and fertilizer N. Applying fertilizer N is considered an aid for boosting the available N in the soil. Studies of nodulated soybeans revealed a considerable yield response to frequent N inputs when the nitrogen fixation system did not meet N demand (Salvagiotti et al., 2008). For soybeans in Ontario, 4 kg N ha^{-1} of N fertilizer was applied to the soil.

4.5.2. Residue N inputs

The nitrogen uptake of soybeans in Canada is estimated from annual production data using an equation containing the sum of the dry matter yield of the product, above-ground residue, and roots multiply by the N concentration of produce, above–ground residue, and roots, respectively. Organic nitrogen in legume residue and root may not be mineralized right away, but would be remineralized within the next year or later (Walley et al., 2007). Yields of soybean can be converted to a dry matter basis based on an estimated moisture content of 0.14. Estimates of dry matter allocation derived from the harvest index and root to shoot ratios are used to calculate the yields of above-ground residues and roots. For example, soybeans grown in Canada typically have a certain harvest index [grain / (grain + above–ground residue)] and a specific root/ (above–ground biomass) ratio. As a result, the dry matter allocation of soybean (grain: above–ground residue: root) was calculated to be 0.30:0.45:0.25. In Canada, the ratio of aboveground residue for soybean is 0.45, the ratio of soybean yield is 0.30, and the aboveground residue N concentration is 0.006 kg N kg^{-1} residue. The ratio of below–ground residue is 0.25, and the belowground residue N concentration is 0.01 kg N kg^{-1} residue (Janzen et al., 2003).

4.5.3. Mineralization N inputs

Because of greater mineralization (conversion to inorganic form) and lower carbon inputs, the conversion of natural ecosystems to farmland in eastern Canada can have drastic effects. Often, the land use changes not only result in a loss of soil organic carbon, and hence a net CO_2 emission, but also a conversion of nitrogen in the soil organic matter to ammonium and nitrate (Gregorich et al., 2005; Penman et al., 2003). Net N mineralization is estimated from the net change in soil carbon. Based on the C:N ratio of 17 at the Sainte-Clotilde experimental farm, Quebec , and annual amounts of N mineralized in the organic soil were estimated from 250 to 571 kg N ha^{-1} (Rochette et al., 2010).

4.5.4. Direct emission

Agricultural production is directly or indirectly responsible for 65% of anthropogenic N_2O sources. In 2018, the Canadian agricultural sector emitted 59 Mt of CO_2-eq in the form of CO_2, N_2O, and CH_4 of the 729 Mt of CO_2-eq emitted by GHGs in Canada. Agricultural soils emit

N_2O, a potent greenhouse gas. Emissions from manure management systems and soils are two important direct agricultural sources of N_2O, and through these sources, N_2O accounts for approximately 36% of agricultural emissions (in CO_2-eq) (Fouli et al., 2021). In Canada, agricultural soils are the most significant single source of N_2O, accounting for half of all anthropogenic emissions. Most N_2O emissions (25 Mt CO_2-eq) arise from agricultural soils via direct and indirect releases into the atmosphere. Nitrification, denitrification, or a combination of both in the soil can produce N_2O. When agricultural activity supplies nitrogen, resulting in the net mineralization of native soil or generating other conditions that boost N_2O production and emission, direct N_2O emissions from agricultural soils increase (Rochette et al., 2008). Based on the amount of N applied to farms and environmental circumstances, the amount of direct and indirect N_2O emissions from agricultural areas can be estimated (Gregorich et al., 2005).

Because soil-related emissions and crop residue decomposition will continue until the soil is frozen, in this study, the growing season was considered from May to October. In addition, precipitation in each agricultural region was analyzed using data from the daily weather data reports of environment and climate change Canada. Table 3 shows the relationship between different latitudes with the DT_{perc} value (Brouwer and Heibloem, 1986).The crop factor (Kc) values and growth stages for soybean are indicated in Table 4 (Irmak et al., 2013). Evapotranspiration data were obtained from the Ontario ministry of agriculture. The temperature and latitude of each crop district were extracted from the daily data report of the meteorological service of Canada.

Table 3. Mean daily percentage (DT perc) of annual daytime hours at different latitudes.

Latitude	May	June	July	August	September	October
40	0.32	0.34	0.33	0.31	0.28	0.25
45	0.34	0.35	0.34	0.32	0.28	0.24
50	0.34	0.36	0.35	0.32	0.28	0.24
55	0.36	0.39	0.38	0.33	0.28	0.23

Table 4. Average grass-reference crop coefficients (Kc) and lengths of crop development stage (LS) for soybean given in FAQ-56.

Soybean	Initial stage	Develop	Mid-season stage	Late season stage
Days	20	30/35	60	25
Crop factor Kc	0.50	-	1.15	0.50

Weather conditions varied substantially within Ontario. Figures 10 and 11 indicate the precipitation (mm) and evapotranspiration (mm) for each region during the growing season. The amounts of evapotranspiration were significantly higher in southern Ontario and western Ontario than in northern Ontario and central Ontario. The average amount of evapotranspiration from May to October was 581 mm. Moreover, the amount of precipitation demonstrated an increasing trend from central Ontario to southern Ontario and a decreasing trend from eastern Ontario to northern Ontario. The average amount of precipitation in the growing season was 497 mm. The calculated direct N_2O emission factors are displayed in Figure 12. The range of emission factors from direct N_2O emission was from 0.011 to 0.019 kg N_2O-N kg^{-1} N. Hamilton County of southern Ontario had the highest EF_{direct} value among all crop districts, while the lowest EF_{direct} value was in Peterborough central Ontario.
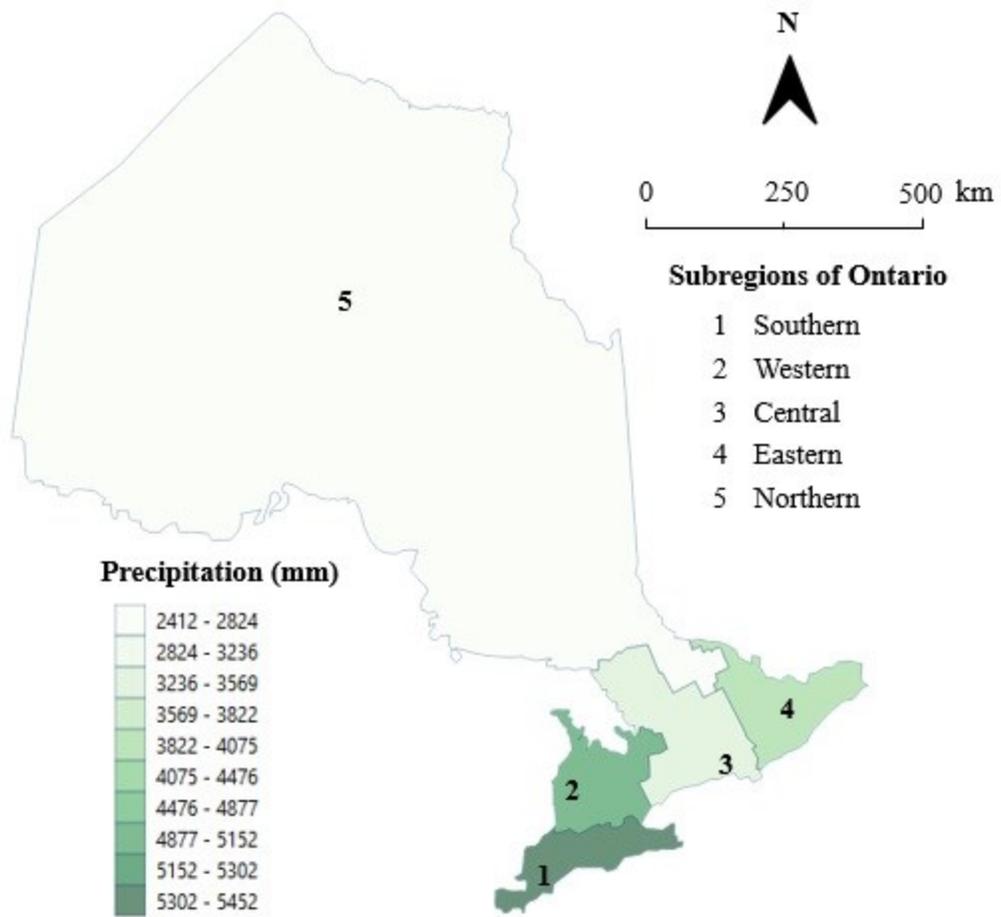
Figure 10. Seeding area precipitation (mm)
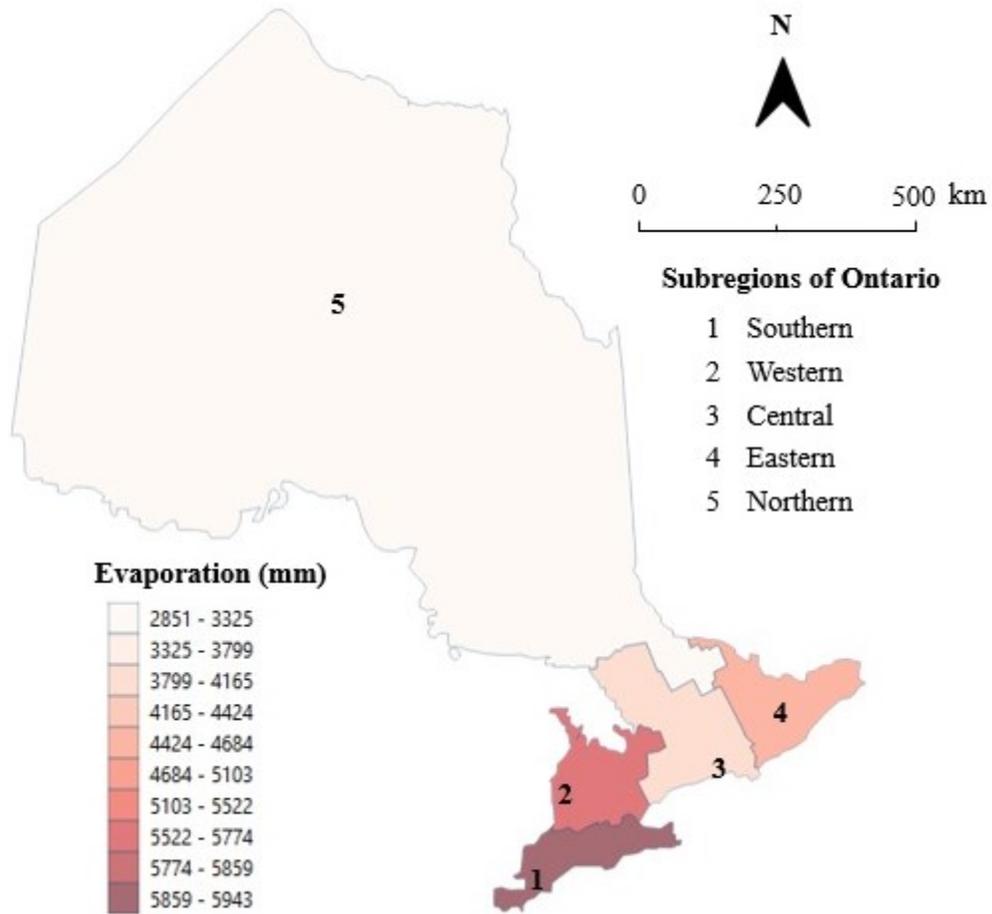
Figure 11. Seeding area evapotranspiration (mm)
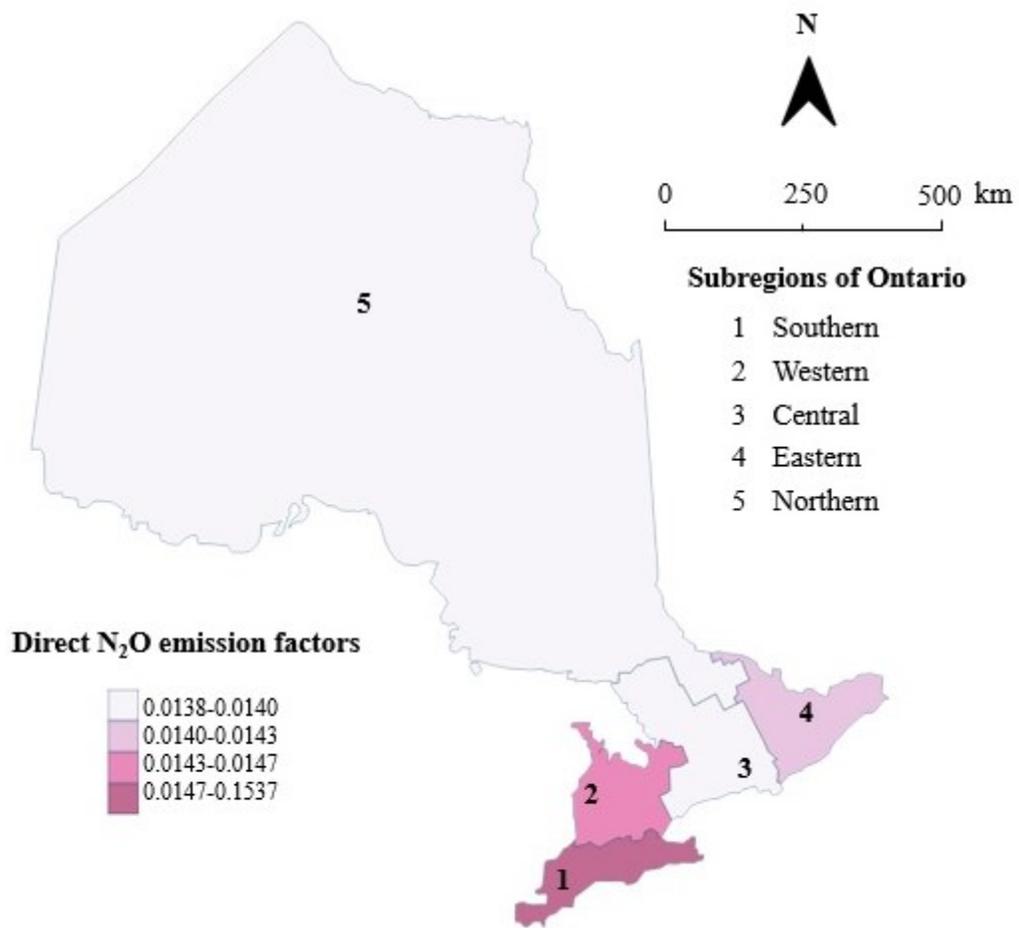
Figure 12. N$_2$O emission factors (EFdirect)

4.5.5. Indirect emission

A portion of the N fertilizer applied to agricultural lands is transferred off-site through volatilization in the form of NH_3 and its subsequent re-deposition or leaching and runoff. The nitrogen from these sources supplies additional N for nitrification and denitrification to generate N_2O. The amount of N volatilized relies on a number of elements, including fertilizer and N application rate, methods and time of usage, soil texture, fertilizer types, soil pH, and temperature. N_2O is estimated using the default IPCC factor of 0.01 kg N_2O-N kg^{-1} N, and the fraction of N lost 0.1 kg N_2O-N kg^{-1}.

Nitrogen leaching from agriculture is of major concern due to its contribution to indirect emissions of GHGs, such as N_2O. This issue is exacerbated in regions with fertilized coarse-textured soils or in counties with high precipitation (Abdalla et al., 2019). When inorganic fertilize, manure, and crop residue are applied to fields, a portion of the N from these sources is lost through leaching and runoff. The magnitude of this loss is determined by a variety of parameters, including the rate and technique of application, rainfall, soil texture, crop type, and landscape. The nitrogen lost can go through subsequent transformations, such as nitrification and denitrification, resulting in N_2O emissions. The amount of N leached varies by area. Leaching losses in humid districts of Canada may exceed 100 kg N ha^{-1}yr^{-1}, while losses in Ontario can range from 0–37 kg N ha^{-1}yr^{-1} (National Inventory Report, 2020). There are fewer leaching losses of N in the Canadian prairies because of the region's high potential evapotranspiration. For the prairie soils, the fraction of N lost via leaching ranged from 0.05–0.1 (Shi et al., 2021). The fraction of N lost through leaching and runoff is multiplied by the amount of fertilizer and crop residue, and by an emission factor of 0.0075 kg N_2O-N kg^{-1}N (IPCC, 2006).

4.6. Total GHG emission

The total GHG emission from soybean production in Ontario is calculated as follows:

$$\sum_{i=1}^{m} GHG_{total,i} = GHG_{farm,i} + GHG_{fert,i} + GHG_{herb,i} + GHG_{input,i}$$

where i is the crop district. The corresponding parameters and their values are shown in Table 5.

Table 5.The parameters used in the calculation of total GHG emission from soybean production

Parameters	Values
GHG emission coefficient for herbicide usage (E_{herb})	23.1 kg CO_2-eq ha^{-1}yr^{-1}
GHG emission coefficient for farming practices (K_{farm})	70.0 kg CO_2-eq ha^{-1}yr^{-1}
GHG emission rate about manufacturing, storage and transportation of N fertilizer (E_{fert_N})	4.8 kg CO_2-eq ha^{-1}yr^{-1}
N fertilizer applied on the farm ($N_{applied}$)	4.0 kg N ha^{-1}yr^{-1}
GHG emission rate about manufacturing, storage and transportation of P fertilizer (E_{fert_P})	7.3×10^{-1} kg CO_2-eq ha^{-1}yr^{-1}
P fertilizer applied on the farm ($P_{applied}$)	18.0 kg P ha^{-1}yr^{-1}
Emission factor from direct emission (EF_{direct})	11.0×10^{-3} - 19.0×10^{-3} kg N_2O-N kg^{-1}N
Fraction of N lost by leaching ($FRAC_{leach}$)	8.57×10^{-2} - 1.80×10^{-1}
N inputs from crop residue to soil (N_{resi}/A)	$0.21 - 0.33$
Emission factor for leaching and runoff (EF_{leach})	7.50×10^{-3} kg N_2O-N kg^{-1}N
Fraction of N lost by volatilization ($FRAC_{volat}$)	1.00×10^{-1}
Emission factor for volatilization (EF_{volat})	1.00×10^{-2} kg N_2O-N kg^{-1}N

4.7. Results and analysis

4.7.1. Contributors to GHG emissions

The total GHG emission intensities of various activities associated with Ontario soybean production in 2018 are shown in Figure 13 and Table 6. The total GHG emission from all five agricultural regions was around 694,944.143 Mg CO_2-eq. The largest emission contributor was agricultural land. The total emission from agricultural land was around 537,474.940 Mg CO_2-eq which accounted for 77 % of the total emission. The GHG emissions from farming operations were the second largest emission contributor, with an emission of 87,873.44 Mg CO_2-eq GHG, which accounted for 13 % of the total emission. The GHG emissions from fertilizer production and delivery and herbicide/pesticide usage were 40,600and 29,000 Mg CO_2-eq, accounting for 6% and 4% of total emission, respectively.

Table 6. Inventory of total GHG emissions

GHG emission contributor	Emission (Mg CO_2-eq)	Emission range (kg CO_2-eq yr^{-1})	% Of the total emission
Fertilizer production and delivery	40597.53	[32.34,32.34]	5.84
Agricultural land	537474.94	[280.20,466.30]	77.34
Farming operation	87873.44	[70,70]	12.65
Herbicide and pesticide Usage	28998.23	[20.8,20.8]	4.17
Total emission	694944.14	[405.64,591.73]	100
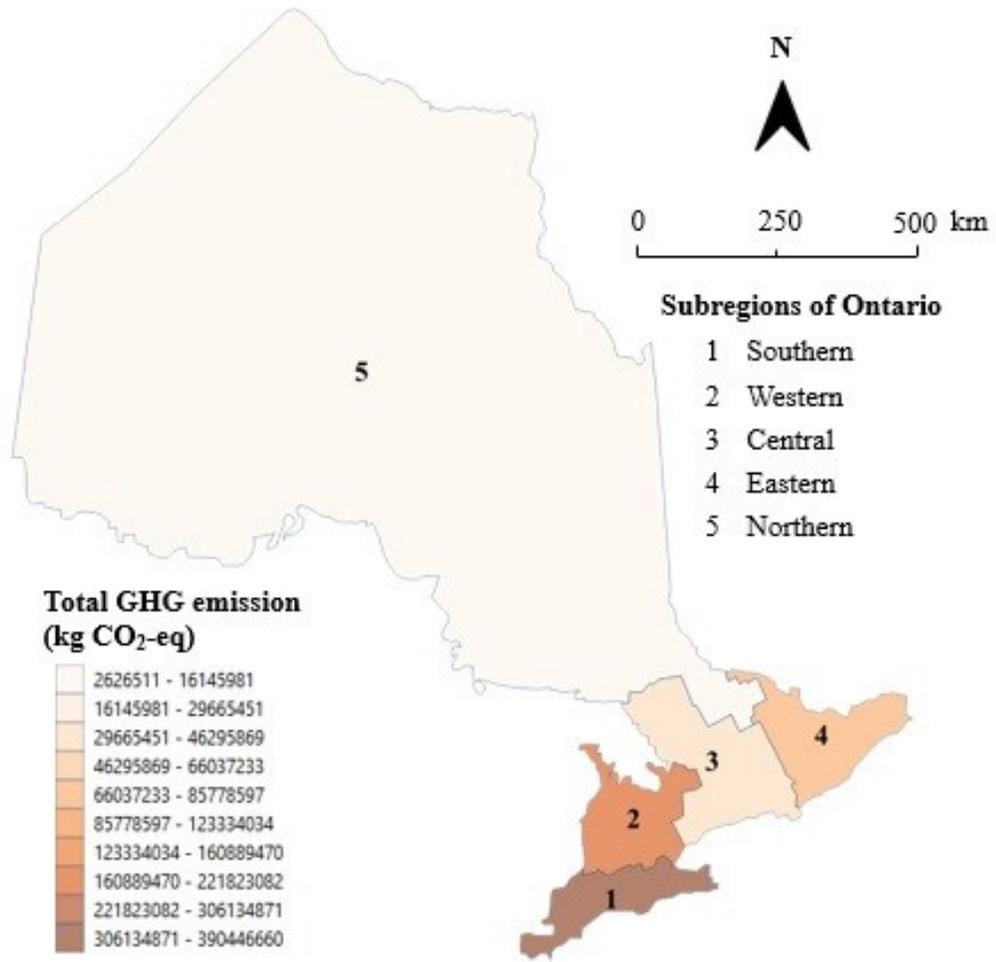
Figure 13. Total GHG emissions for each region of Ontario.

The patterns of GHG emissions in each agricultural region varied from one to other (Figure 14). The average GHG emissions of these regions ranged from 405.64 to 591.73 kg CO_2-eq ha^{-1}. Among the 40 crop districts, the major contributors to GHG emissions were agricultural land, which accounted for 64%–83% of the total emissions from each region (65%–78% among five agricultural regions). The emissions from farming practice accounts for 10%–20% of total emissions from the crop districts (12%–19% in five regions).

GHG emissions from fertilizer production, transportation, storage, and delivery accounted for 4%–9% of total emissions in these districts (5.6%–9% in five regions), and the remaining 3%–7% of the total emissions were related to the herbicides and fungicides (4%–6% in five regions). A further analysis of the emissions from agricultural land revealed that the direct emissions from agricultural land accounted for another 56%–73% of the total emissions (56%–69% in five regions). Because of the differences in soil and environmental conditions in these crop districts, the ratios vary. The indirect emissions were relatively steady with a range of 8% to 10% of the total emissions (8.4%–9.6% in five regions).
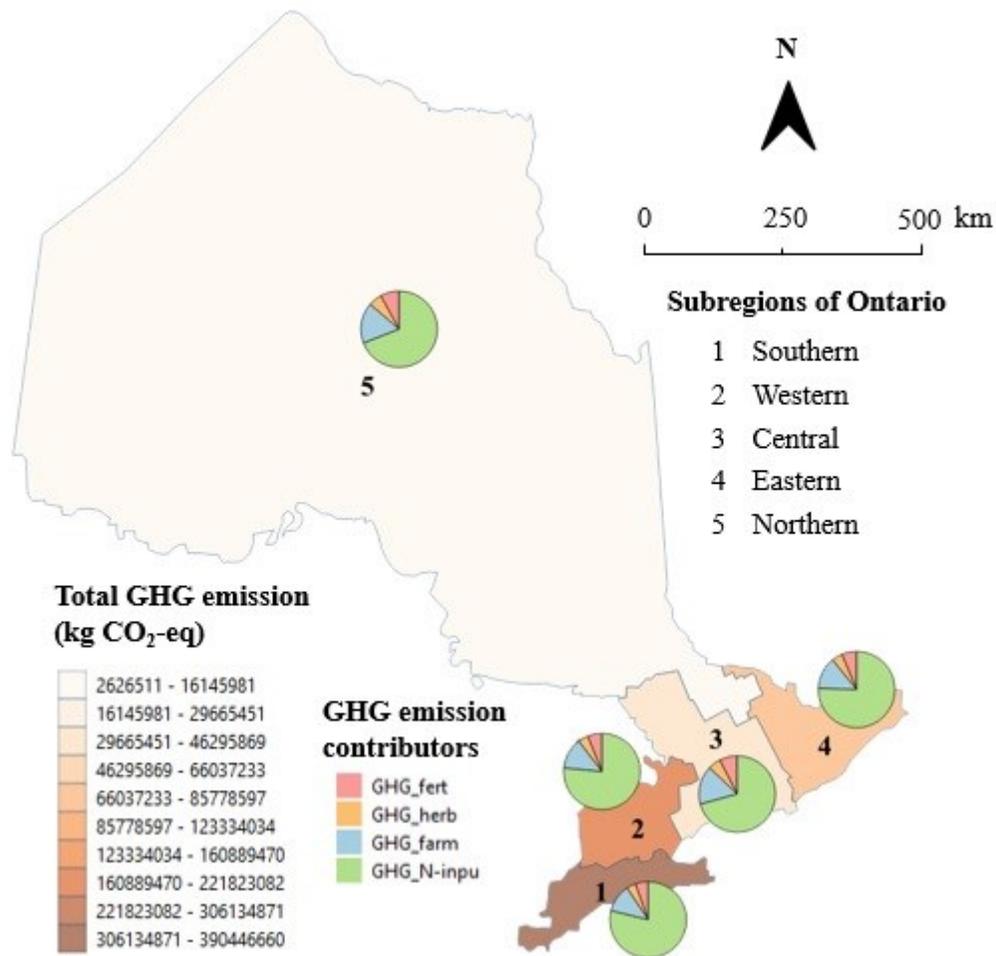
Figure 14. Total GHG emissions and emission contributor for each agricultural region (GHGsN: GHG emissions from agricultural land; GHGsfarm: GHG emissions from farming operation; GHGsherb: GHG emissions from herbicide and pesticide usage; GHGsfert: GHG emissions from N and P fertilizer production and delivery).

4.7.2. Emission contributors and environmental effects

4.7.2.1. Geographic variability of GHG emissions in crop districts

Environmental conditions can have an impact on GHG emissions. The crop districts were divided into five categories based on the ratio of precipitation to evaporation, as indicated in Table 7. The ratios of precipitation to evaporation (Pr/PE) in these districts are also shown in Figure 15. The values of Pr/PE were higher in southern and western Ontario compared with those in northern and eastern Ontario. The percentage of GHG emissions associated with N_2O decreased from the western to the eastern region, while precipitation declined slightly. Soybean grown in Lambton of southern Ontario had the highest GHG emissions with 609 kg CO_2-eq ha^{-1}, which was around 1.5 times the emission from Sudbury of northern Ontario (416 kg $CO_{2\text{-eq}}$ ha^{-1}) (Figure16).

The average area GHG emissions from northern, central, eastern, western, and southern Ontario were 405.64, 429.00, 512.48, 533.68, and 591.73 kg CO_2-eq ha^{-1}, respectively (Table 8). The emission from southern Ontario (high Pr/PE) was 46% greater than that from northern Ontario (low Pr/PE). The total GHG emissions from the western Ontario was 4.13% greater than that from eastern Ontario, and 31.5% higher than that from northern Ontario. Due to changing environmental conditions, total GHG emissions decreased from southern Ontario to central Ontario.

Table 7. Categorized crop districts in Ontario.

Grouped Area	Pr/PE	Crop Districts
Dry area	0.846–0.852	Northern Ontario
Relative dry area	0.852–0.863	Central Ontario
Normal area	0.863–0.876	Eastern Ontario
Relative wet area	0.876–0.892	Western Ontario
Wet area	0.892–0.917	Southern Ontario
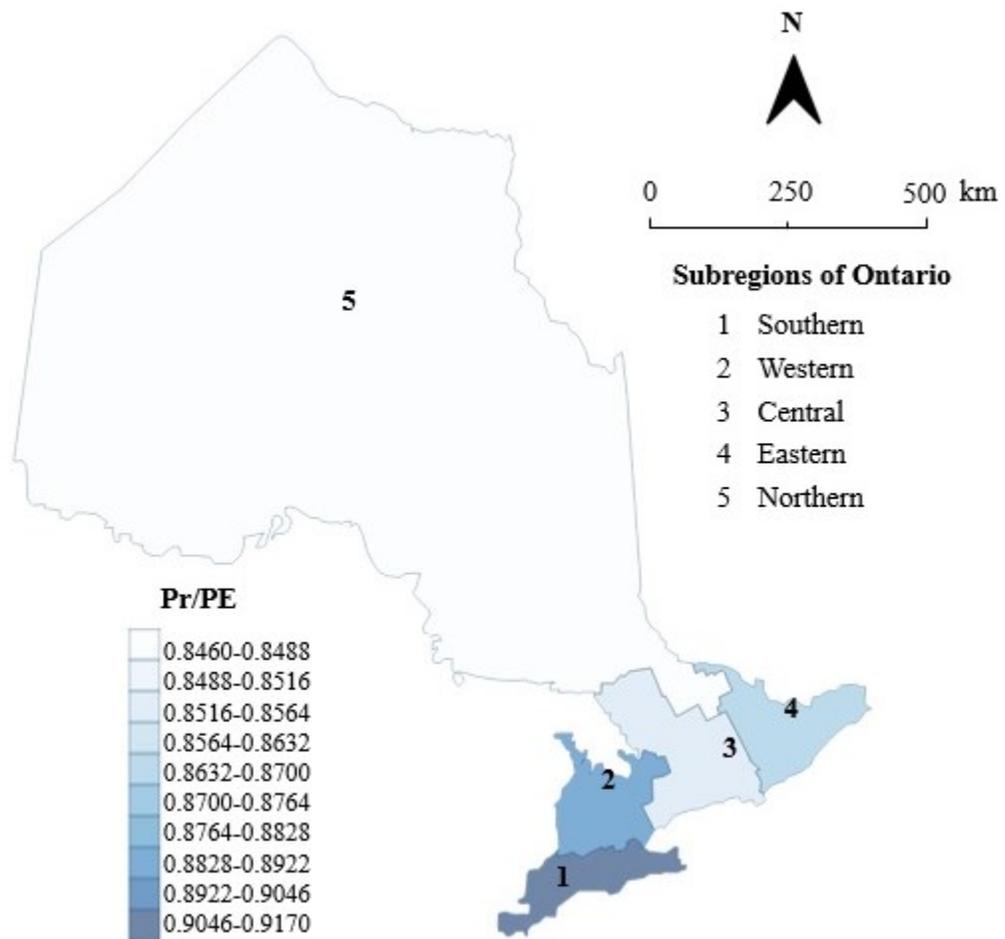
Figure 15. Categorized crop districts in Ontario.

Table 8. GHG emissions from fertilizer production and application in different regions of Ontario.

Categorized area	Total emissions (kg CO_2-eq ha^{-1})	Emission from N, P fertilizer production & delivery		Emission from N fertilizer application		% (production, delivery, and application)
		(kg CO_2-eq ha^{-1})	%	(kg CO_2-eq ha^{-1})	%	
Dry	405.64	32.34	7.97	280.20	69.07	77.04
Relatively dry	429.00	32.34	7.54	303.17	70.73	78.27
Normal	512.48	32.34	6.31	387.04	75.52	81.83
Relatively humid	533.68	32.34	6.06	408.23	76.49	82.55
Humid	591.73	32.34	5.46	466.30	78.80	84.26
Average	495.00	32.34	6.53	369.00	74.12	80.65

The production, transportation, storage, and delivery of N and P fertilizers, as well as their use, are the main contributors to total GHG emissions (Figure16). As shown in Table 8, in high Pr/PE, the emission from fertilizer accounts for 84.26% of total emissions, while in low Pr/PE, the emission from fertilizer production and application account for 77% of total emissions, and the emission from fertilizer application accounts for 69.07%. In normal area, emission from N fertilizer application is less than relatively humid area although emission from fertilizer production shows higher percentage. The average total emission from fertilizer is about 500 $kgCO_2$-eq ha^{-1}, of which emission from N fertilizer application accounts for 74.12% and emission from fertilizer production and delivery accounts for 6.53% of the total.
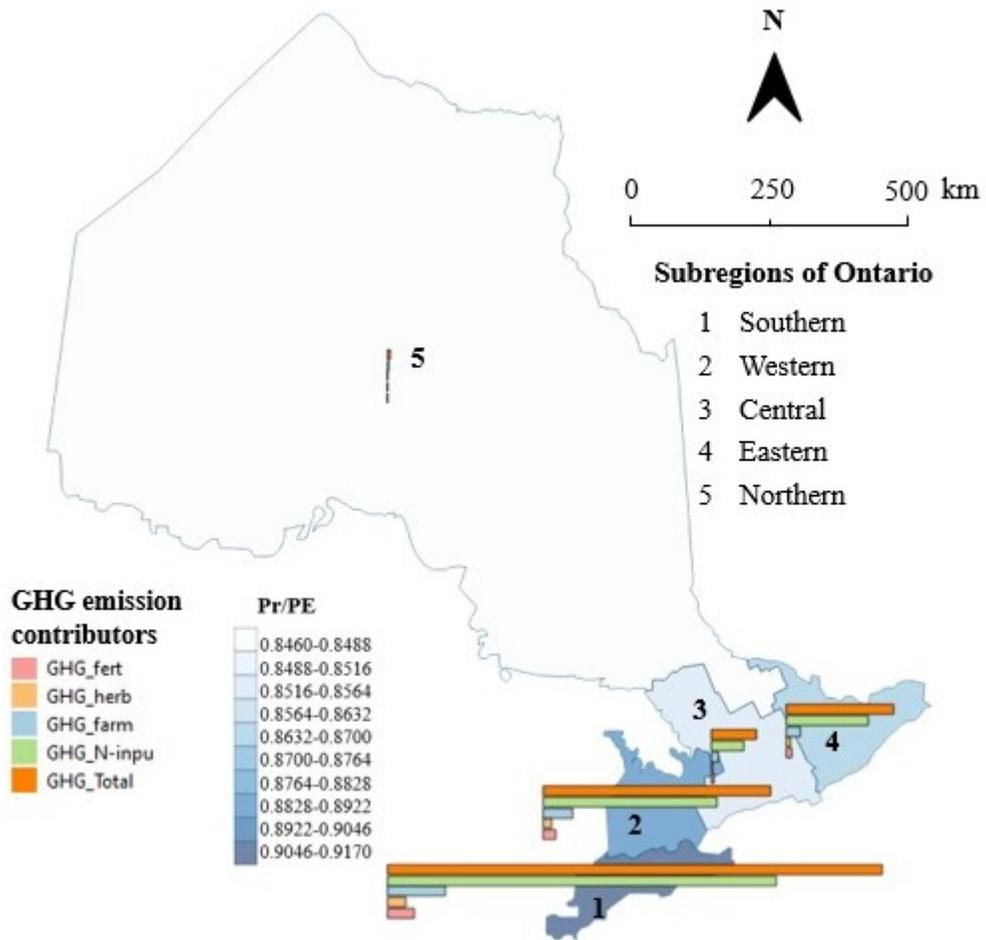
Figure 16.Total GHG emissions from different sources (GHGsN: GHG emissions from agricultural land; GHGsfarm: GHG emissions from farming operation; GHGsherb: GHG emissions from herbicide and pesticide usage; GHGsfert: GHG emissions from N and P fertilizer production and delivery)

4.7.2.2. GHG emissions related to N fertilizer

The manufacture and application of N fertilizer is responsible for around 70% of the GHG emissions associated with producing and harvesting soybeans. As shown in Table 9, the emission intensity from N fertilizer application is the largest contributor, taking an average of 65% of the total GHG emission related to N fertilizer. The average emission from the manufacture and delivery of N fertilizer accounts for roughly 4.09% of total emission. The emissions associated with farming practices and pesticide use are much lower than the emission related to N fertilizer use. Diesel used during farming operations contributed 14.44% of total GHG emissions which is almost three times more than emissions from pesticide use (including fungicides). The contribution from P fertilizer to GHG emissions is minor and is less than 3% of total emissions. The GHG emissions from the usage of N fertilizer is 4.78 times that of various farming operations and 13.07 times the emission from herbicide supply, based on the average values of the five regional categories. According to many recent studies, increased nitrogen fertilizer enhances crop productivity and the quantity of carbon in soil. Furthermore, a significant amount of plant residue carbon can be stored in more stable soil organic-mineral complexes (Gan et al., 2014).

4.7.2.3. GHG emissions from agricultural land

Table 10 and Figure 17 describe GHG emissions from fertilizer production and delivery, application of pesticide, farming operation, and agricultural land. It is clear that the emissions from all five regions are mainly caused by agricultural land, which accounts for more than 60% of total emissions. High Pr/PE area has the highest percentage of emission. In low and relatively low Pr/PE, around 8% of total emission is derived from fertilizer production and delivery, while, normal, relatively high Pr/PE, and high Pr/PE have emission of 6.31%, 6.06%, and 5.46%, respectively. Emissions associated with herbicide usage and fertilizer production are lower than those from farming practices. The contribution from herbicide and fungicide production and delivery is minor among the different activities, at less than 5% of the total emissions. From dry to humid areas, the percentage of the emission from herbicide and fungicide production over the total emission is decreasing because there is a significant increase of emissions from other sources. Based on the average values of the five regions, GHG emissions from agricultural land

is 11.35 times the emission from fertilizers supply and 17.64 times the emission from herbicide use.

The average emission rate from pesticide and herbicide application is 20.79 kg CO_2-eq ha^{-1}, which is 4.2% of the total emission. From dry to humid areas, the percentage of GHG emissions from fertilizer and pesticide production decreases, whereas GHG emissions from agricultural land increases. The emission related to various farming operations such as sowing, spraying, windrowing, and harvesting crops contribute to 14.44% of total emission. Using the variables of 14, 14, 5, and 37 kg CO_2-eq ha^{-1} for tillage planting, no-tillage planting, herbicide and fungicide spraying, and harvesting, the average emission from farming operation is estimated to be 70 kg CO_2-eq ha^{-1}(Lal, 2004a).

4.7.2.4. Direct and indirect GHG emissions from cropping land

Mineralization N inputs, residue and fertilizer are the main sources of direct and indirect emissions. The environmental conditions and quantity of nitrogen applied can have an effect on direct and indirect emissions. In low Pr/PE, the proportion of N_2O emissions drops. This is because the amount of straw and root biomass produced can be affected by variations in Pr/PE. Soybeans grown in the dry area (northern Ontario) produced an average biomass (above ground and below ground) of 161.09 kg ha^{-1}, which was significantly less than that produced in the relatively wet (407.70 kg ha^{-1}) and wet (476.47 kg ha^{-1}) areas. The emissions from crop residue decomposition accounted for 49.5%, 46.9%, 53.3%, 54.5%, and 58.3% of the total emission in the dry area, relatively dry area, normal area, relatively humid area, and humid area, respectively. Soybean residues decomposition provided the nitrogen source for nitrification and denitrification and resulted in 262.33kg CO_2-eq ha^{-1} (52.5% of the total emission) for both direct and indirect emissions. Emissions from residue decomposition in the relatively dry area (201.30 kg CO_2-eq) was not much greater than that from the dry area (201.18 kg CO_2-eq), but it was significantly less than that from the relatively humid (290.90 kg CO_2-eq) and humid (345.15 kg CO_2-eq) area of Ontario (Table11). N_2O is mainly produced during denitrification, which is influenced by soil moisture (Gan et al., 2012c). The results show that the proportion of soybean residue decomposition emission will increase with increased rainfall (Figure18).

Fertilizer N is emitted in agricultural land via volatilization, leaching and runoff (indirect emission) and direct emission (Table12). The average GHG emissions per area from direct emission is 323.66 kg CO_2-eq ha^{-1}. GHG emissions from direct emission increased from 244.88 kg CO_2-eq ha^{-1} to 409.78 kg CO_2-eq ha^{-1}, from dry to humid areas, and its proportion of total GHG emission grew from 60.36% to 69.25%. In the low Pr/PE area, direct emissions accounted for only about 60% of total emissions, while in the high Pr/PE area, direct emissions accounted for around 70% of total emissions. Furthermore, GHG emissions from leaching and runoff in the humid region were almost more than 1.5 times as high as their emission in dry area. The amount of direct and indirect emission varied under various environmental circumstances, impacted by the total straw and root biomass. When there is a greater amount of straw and root biomass, there will be more total emission derived from the decomposition of the crop residues (Figure19).

For all crop districts, GHG emissions per area from fertilizer, pesticide, and farming activities were assumed to be the same. The indirect emissions in the crop regions accounted for 8.70%, 8.76%, 9.28%, 9.31%, and 9.55% of the total emission from dry, relatively dry, normal, relatively humid, and humid areas, respectively (Table 12). Leaching and runoff held major portion of indirect emissions. Based on the values in Table 12, the leaching emission from the relatively high Pr/PE area (western Ontario) was around 34% greater than that from the relatively low Pr/PE area (central Ontario). The GHG emissions from volatilization is 1.87 kg CO_2-eq ha^{-1} in all regions while dry area has the lowest leaching and runoff emissions, and wet area shows the highest emission.

The GHG emissions from farming activity and pesticide consumption were not high, accounting for about 12.64% and 4.17% of the total emission, respectively. The highest fraction of N lost by leaching (FRAC$_{leach}$) is 0.272 in the humid area of Ontario, while the lowest fraction is seen in the dry area. The results show EF and FRAC$_{leach}$ increase by increasing Pr/PE. From dry to humid areas, N_2O emissions increases from 280.20 to 466.30 kgCO_2-eq ha^{-1}. Moreover, N_2O emissions in normal area is 38% greater than dry area while humid area shows more emissions which is 21% greater than it (Table13).

4.7.2.5. GHG emissions based on crop yield

GHG emissions was further analyzed based on crop yield. The average GHG emissions from the dry area, relative dry area, normal area, relative wet area, and wet area were 179.80, 212.39, 191.13, 189.18, and 185.11 kg CO_2-eq t^{-1} of grain, respectively (Table14). From central Ontario, GHG emissions was 212.39 kg CO_2-eq t^{-1} of grain, which is 3% greater than in the dry area. The soybean produced in Chatham-Kent in southern Ontario had the highest GHG emissions of 165 kg CO_2-eq t^{-1} of grain, 41 times higher than soybean produced in Greater Sudbury in northern Ontario. However, higher GHG emissions based on crop yield are not always associated with higher GHG emissions per area in these agricultural regions. The GHG emissions per area from southern Ontario (591.73 kg CO_2-eq ha^{-1}) was greater than it from eastern Ontario (512.48 kg CO_2-eq ha^{-1}). In comparison, GHG emissions per ton of grain produced in southern Ontario (185.11 kg CO_2-eq t^{-1}) is lower than that in the eastern Ontario (191.13 kg CO_2-eq t^{-1}). These differences could be due to the fact that Ontario's soil texture varies spatially.

Table 9. GHG emissions relating to N fertilizer and other activities in different regions of Ontario.

Categorized area	Total emissions (kg CO_2-eq ha^{-1})	Emission related to N fertilizer			Emission related to input other than N fertilizer		Farming operation
		N fertilizer production (%)	N fertilizer application+ Residue soil N+ Mineralized soil N (%)	Subtotal	P fertilizer production (%)	Herbicide and fungicide production %	%
Dry	405.64	4.78	60.36	65.14	3.27	5.69	17.26
Relatively Dry	429.00	4.62	61.97	66.59	3.17	5.39	16.33
Normal	512.48	3.83	66.24	70.07	2.62	4.50	13.66
Relatively Humid	533.68	3.66	67.18	70.84	2.50	5.39	13.12
Humid	591.73	3.54	69.25	72.79	2.43	3.90	11.83
Average	495.00	4.09	65.00	69.09	2.80	4.97	14.44

Table 10. GHG emissions from different activities

Categorized area	Total emissions (kg CO_2-eq ha^{-1})	N and P fertilizer production & delivery		Agricultural land		Herbicide and fungicide production & delivery		Farming operation	
		Emission (kg CO_2-eq ha^{-1})	%	Emission (kg CO_2-eq ha^{-1})	%	Emission (kg CO_2-eq ha^{-1})	%	Emission (kg CO_2-eq ha^{-1})	%
Dry	405.64	32.34	7.79	280.20	69.07	20.79	5.12	70.0	17.25
Relatively Dry	429.00	32.34	7.54	303.17	70.73	20.79	4.84	70.0	16.32
Normal	512.48	32.34	6.31	387.04	75.52	20.79	4.05	70.0	13.66
Relatively Humid	533.68	32.34	6.06	408.23	76.49	20.79	3.89	70.0	13.12
Humid	591.73	32.34	5.46	466.30	78.80	20.79	3.51	70.0	11.83
Average	495.00	32.34	6.53	369.00	74.12	20.79	4.20	70.0	14.14
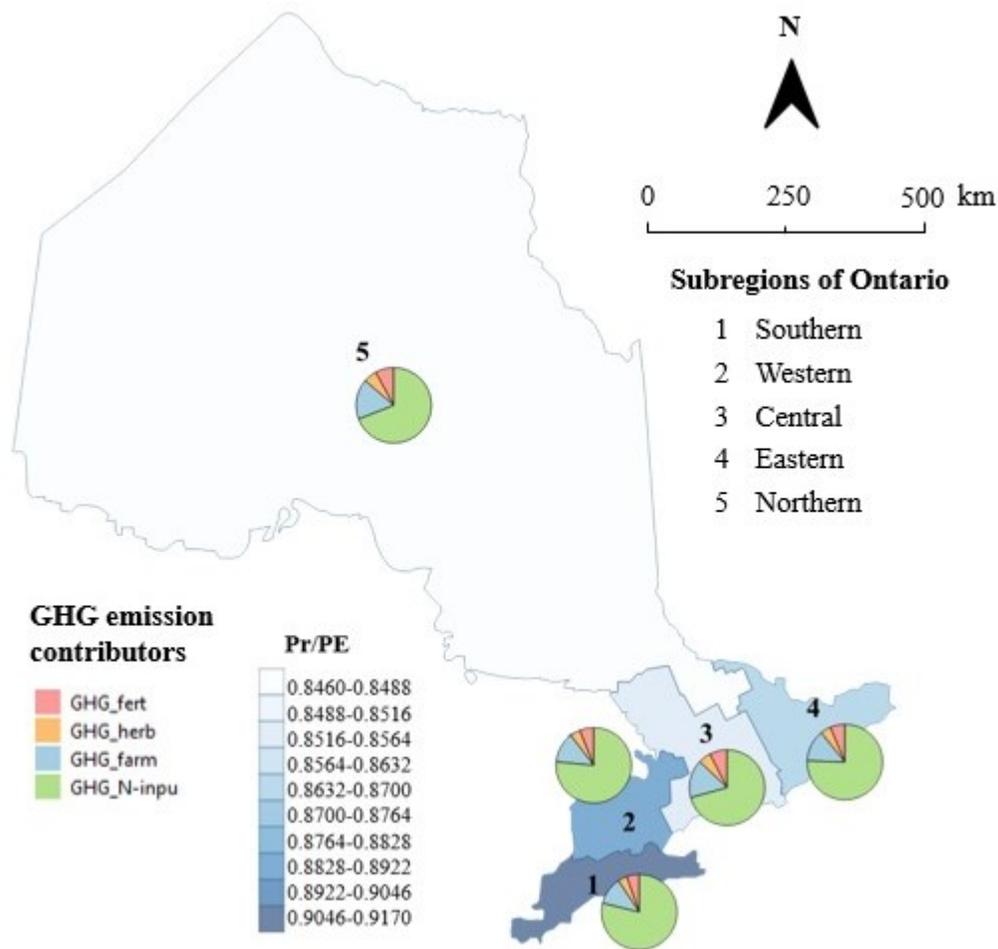
Figure 17. Emission contributor in categorized areas (GHGsN: GHG emissions from agricultural land; GHGsfarm: GHG emissions from farming operation; GHGsherb: GHG emissions from herbicide and pesticide usage; GHGsfert: GHG emissions from N and P fertilizer production and delivery).

Table 11. Emission from N inputs in crop districts of Ontario.

Categorized Area	Total emissions (kg CO_2-eq ha^{-1})	Emission from N fertilizer application		Emission from residue N decomposition		Total %
		(kg CO_2-eq ha^{-1})	%	(kg CO_2-eq ha^{-1})	%	
Dry	405.64	79.02	19.48	201.18	49.5	68.98
Relatively Dry	429.00	101.87	23.74	201.30	46.9	70.65
Normal	512.48	113.90	22.22	273.14	53.3	75.52
Relatively Humid	533.68	117.33	21.98	290.90	54.5	76.48
Humid	591.73	121.15	20.47	345.15	58.3	78.77
Average	495.00	106.67	21.55	262.33	52.5	74.05
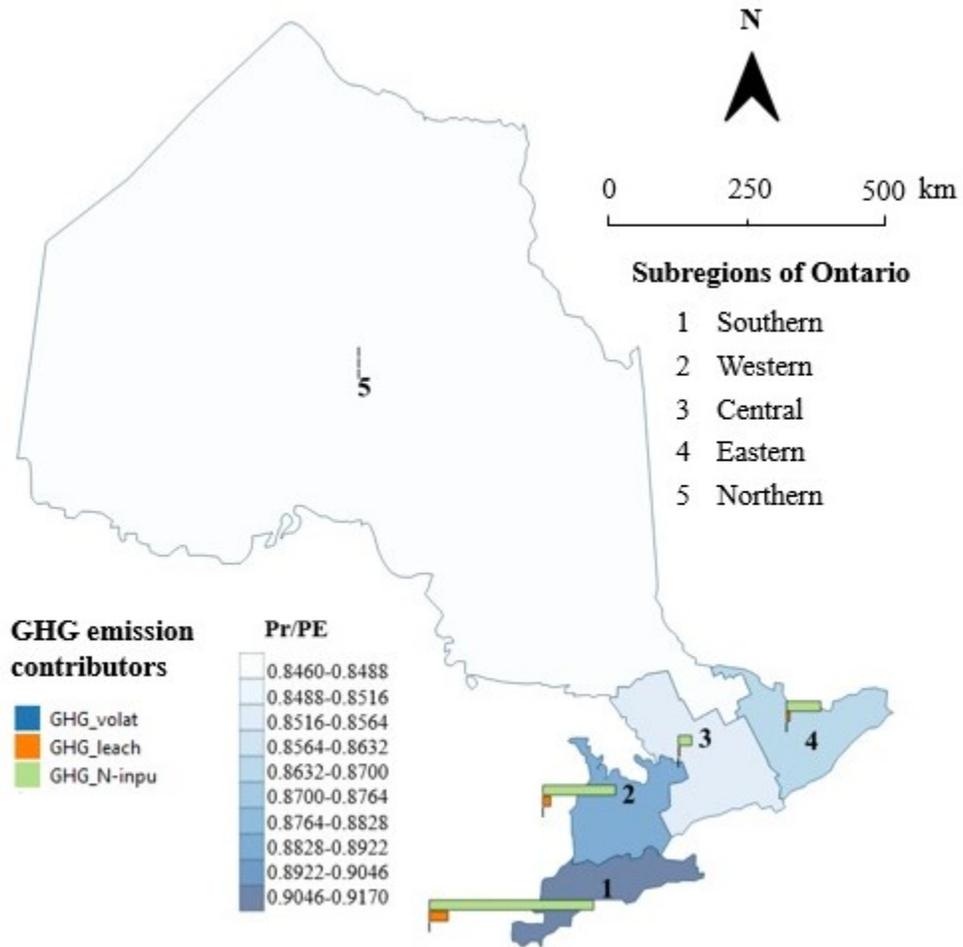
Figure 18. Direct and indirect (Volatilization + Leaching) emissions. GHGsleach: GHG emissions from N leaching caused by fertilizer N, Residue N and Mineralized N; GHGsvolat: GHG emissions from volatilization caused by fertilizer N application; GHGsinput: GHG emissions from direct and indirect emission caused by fertilizer N, Residue N and Mineralized N.

Table 12. Direct and indirect emission in crop regions.

Crop district	Indirect Emission				Direct Emission (kg CO_2-eq ha^{-1})	
	Volatilization (kg CO_2-eq ha^{-1})	Leaching and runoff (kg CO_2-eq ha^{-1})	Total (kg CO_2-eq ha^{-1})			
	value	value	value	% Of total emission	value	% Of total emission
Dry	1.87	33.44	35.31	8.70	244.88	60.36
Relatively Dry	1.87	35.68	37.55	8.76	265.62	61.97
Normal	1.87	45.70	45.57	9.28	339.48	66.24
Relatively Humid	1.87	47.81	49.68	9.31	358.56	67.18
Humid	1.87	54.63	56.50	9.55	409.78	69.25
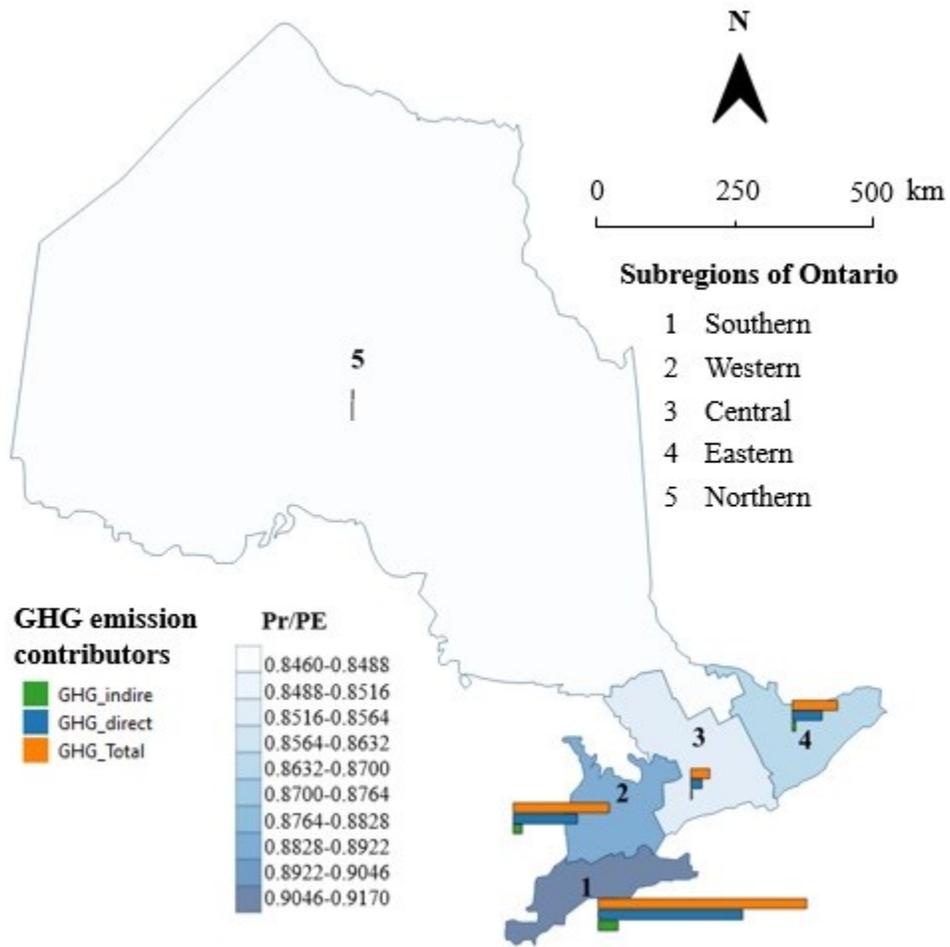
Figure 19. Direct and indirect GHG emissions.

Table 13. N_2O emission factor and its relationship to climate factor.

Crop district	Pr/PE	EF	$FRAC_{leach}$	N_2O Emissions ($kgCO_2\text{-}eq\ ha^{-1}$)
Dry	0.846	0.0138	0.249	280.20
Relatively Dry	0.853	0.0140	0.252	303.17
Normal	0.869	0.0143	0.257	387.04
Relatively Humid	0.886	0.0147	0.263	408.23
Humid	0.917	0.0153	0.272	466.30

Table 14. GHG s mission based on crop yield.

Agricultural region	Soybean production (kg ha^{-1})		GHG emissions per ton of grain (kg CO$_2$-eq ton^{-1})		GHG emissions per area (kg CO$_2$-eq ha^{-1})
	Value	Mean	Value	Mean	Value
Central	14189.98	2027.14	1486.74	212.39	429.00
Southern	31964.44	3196.44	1851.07	185.11	591.73
Northern	10807.25	2161.45	281.81	179.80	405.64
Eastern	19240.54	2405.06	1529.03	191.13	512.48
Western	27351.01	2735.10	1891.83	189.18	533.68
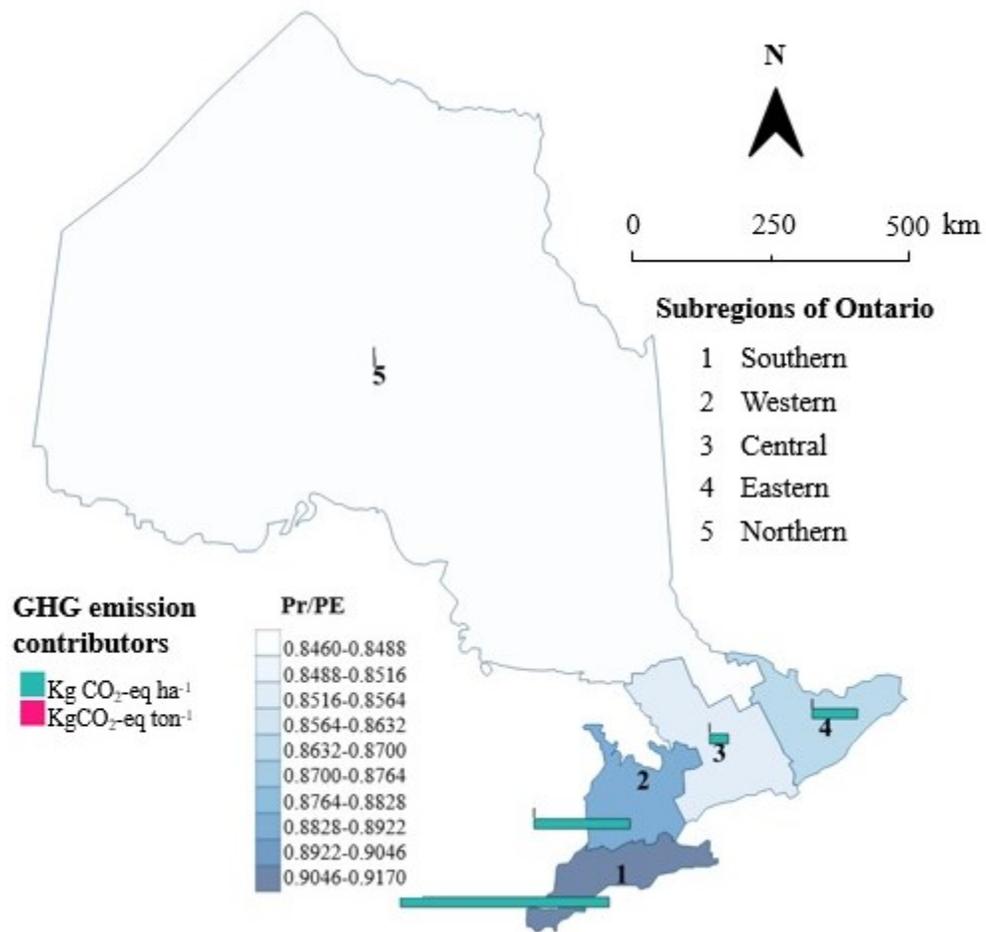
Figure 20. GHG emissions based on crop yield

CHAPTER 5. FACTORIAL-BASED SENSITIVITY ANALYSIS

5.1. Parameter uncertainties

The impact of uncertainty inputs on modeling results was investigated using an analysis of uncertainty and sensitivity (Asif and Chen, 2020).The results can be used to judge whether there is an acceptable level of precision from the system (Shrestha and Wang, 2020). Uncertainty analysis can also help to obtain a better understanding of environmental systems (Li et al., 2020). In the present study, eleven uncertain parameters, including EF_{direct}, EF_{leach}, $FRAC_{leach}$, N_{min}, N_{res}/A, E_{herb}, E_{fert_N}, E_{fert_P}, $N_{applied}$, $P_{applied}$ and K_{farm}, were considered. Their variability ranges and other important elements are discussed below.

5.1.1. Emission factor from direct emission (EF$_{direct}$)

For organic soils in a temperate climate (IPCC, 2006), the default emission factor proposed for national inventories of soil N_2O emissions is 8 kg N_2O-N ha^{-1} yr^{-1}. While North American field data are limited (Rochette et al., 2010). The IPCC has established a broad framework for calculating the emission of greenhouse gases (including N_2O) at the national level. The applied N and a particular emission factor per source category were multiplied to calculate direct N_2O emissions from fertilized soils. For all fertilizer and manure types, application techniques, and land use, the default emission factor for applied fertilizer is 0.01 kg N_2O–N kg^{-1} N applied. This emission factor was obtained from the data-set of 1125 emission factors of Stehfest and Bouwman (Velthof and Mosquera, 2011). The IPCC, (2006) utilized 0.01 kg N_2O-N kg^{-1} N in Tier I methodology to estimate the national inventories of agricultural soil N_2O emissions. This is close to the emission factor of 0.012 kg N_2O-N kg^{-1} N for the average growing season in eastern Canada (Gregorich et al., 2005). The N_2O emission factors, on the other hand, were found to be 4–10 times lower than those in eastern Canada (Rochette et al., 2008). The use of IPCC default emission factor may lead to an overestimation of emissions in western Canada. Furthermore, it could also result in the underestimation of crop GHG emissions in eastern Canada, when spring thaw emissions are considered (Wagner-riddle et al., 2007).

According to Rochette, EF values were 0.0016 kg N_2O-N kg^{-1} N in the semi-arid brown soil zones, and 0.008 kg N_2O-N kg^{-1} N in the sub-humid black soil zones of the Prairie region,

and 0.017 kg $N_2O\text{-}N$ kg^{-1} N in the humid provinces of Quebec and Ontario had. Based on the calculation in Ontario for 2018, the range of EF is $[1.6 \times 10^{-2}, 1.1 \times 10^{-2}]$ kg $N_2O\text{-}N$ kg^{-1} N. For better determination of the uncertainty of this factor, the range of $[1.60 \times 10^{-3}, 1.60 \times 10^{-2}]$ kg $N_2O\text{-}N$ kg^{-1} N was used.

5.1.2. Emission factor for leaching and runoff (EF_{leach})

After application, a portion of fertilizers leaches while the rest is volatilized. These nitrogen losses are described as indirect N_2O emissions (Ho, 2011). In IPCC methodology, the N_2O emission factor EF_{leach} associated with leaching and runoff is the greatest agricultural N_2O emission factor (Nevison, 2000). The emission factor for leaching is 0.0075 kg $N_2O\text{-}N$ kg^{-1} N, according to the IPCC (IPCC, 2006). For all Canadian soil types, Ho, (2011) used 0.0125 kg $N_2O\text{-}N$ kg^{-1} N as EF_{leach}. Leaching emission was calculated using 0.0075 in this study. The range of EF_{leach} was chosen as $[7.50 \times 10^{-3}, 1.25 \times 10^{-2}]$ kg $N_2O\text{-}N$ kg^{-1} N for the uncertainty analysis.

5.1.3. Fraction of N lost by leaching ($FRAC_{leach}$)

With excessive or poorly timed irrigation, readily available N sources such as ammonium nitrate will be readily leached, and present a potential hazard for the environment, as ammonium is rapidly nitrified. Leaching and runoff emissions could be responsible for 1/4 of the total agricultural N_2O emissions. Leaching losses can be extremely variable depending on the intensity and distribution of rainfall, the amount and location of the soil, and fertilizer N in the profile. In general, there is a positive relationship between fertilizer N applied and nitrate-leaching losses (Agostini et al., 2010). A previous study used IPCC-specified minima, maxima and most likely (i.e., default) values for its uncertainty analysis. The default fraction of fertilizer and manure N lost to leaching and surface runoff (kg N/kg fertilizer or manure N) was 0.3, and 0.1–0.8 was considered as the range (Brown et al., 2001).

IPCC (1996) used a default value of 0.3 and a range of 0.1–0.8 for $FRAC_{leach}$. In regions where rainfall is much lower than potential evapotranspiration, $FRAC_{leach}$ can be as low as 0.05. The Prairie region is known for its dry climatic conditions (Rochette et al., 2008). Accordingly, the value of $FRAC_{leach}$ could range from 0.05 to 0.3, with values less than 0.05 being set to 0.05 and those more than 0.3 being set to 0.3 (Gan et al., 2011).The calculation for Ontario showed

that the range of $FRAC_{leach}$ was $[2.09×10^{-1}, 2.91×10^{-1}]$. Considering both ranges, $FRAC_{leach}$ was eventually set to $[5.00×10^{-2}, 3.00×10^{-1}]$.

5.1.4. Volatilization of NH$_3$ and NOx (FRAC$_{volat}$) and the volatilization Emission Factor (EF$_{volat}$)

An average of 10–14% of N is lost via volatilization from synthetic fertilizers (Bouwman et al., 2002b). In 2014, the global demand for N fertilizers was approximately 112 million tons of nitrogen (Pan et al., 2016).Thus, using the average value (10–14%) for volatilization from applied N, 11.2–15.7 million tons of fertilizer-N were lost as NH_3-N worldwide (Zhang et al., 2018).

Indirect N_2O emissions occur when N is lost through NH_3 volatilization or nitrate leaching and then conversion into N_2O in a different location (VanderZaag et al., 2011). NH_3 is a type of nitrogen lost through volatilization, which is one of the main pathways of N loss in agricultural systems (Singh et al., 2013). $FRAC_{volat}$ is 0.1 and EF_{volat} is 0.01 kg N_2O-N kg^{-1} N, according to IPCC, (2006). Soil texture and location have a minor impact on these values.

5.1.5. Mineralization N inputs (N_{min})

Under optimal conditions in the laboratory, rates of N mineralization range from 0.3 to -2.5 µg g^{-1} d^{-1} in mineral soils and from 3.0 to 15 µg g^{-1} d^{-1} in organic layers (Gregorich et al., 1994). According to Kaboneka et al. (1997), net N mineralization was observed only in soybean residue in both Taloka (17.1 mg N/kg) and Leadvale (2.4 mg N/kg) soils, whereas corn and wheat residues showed net N immobilization throughout the incubation study. The highest N mineralization was recorded for soybean residue in Taloka soil.

Rivest et al. (2009) conducted an experiment in southwestern Quebec, and soil N mineralization was determined at two separate periods corresponding to different soybean reproductive stages: (1) from flowering to pod formation (R1–R4), and (2) during grain filling (R5–R6). In 2005, net N mineralization in R1–R4 was 0.91 mg kg^{-1} d^{-1}and 1.09 mg kg^{-1} d^{-1}, while in R5–R6 mineralization was 0.98 mg kg^{-1} d^{-1} and 0.96 mg kg^{-1} d^{-1}. They reported 0.41, 0.6, 0.84, and 0.94 mg kg^{-1} d^{-1} N mineralization for R1–R4 and R5–R6 in 2006, respectively.

Soon and Arshad (2002) conducted a no-tillage experiment in Alberta and found that the average net N mineralization from straw was 5.6 kg N ha^{-1}, and the net N mineralization from the roots varied between 0.9 and 1.6 kg N ha^{-1}. The average N mineralized from straw and root together was 7 kg N ha^{-1}, therefore N_{min} is [0.9, 7.0] kg N ha^{-1} for this study.

5.1.6. Average area total N inputs from crop residue returned to soil (Nres/A)

Soybeans are grown mostly in eastern Canada, and the straw/grain ratio for soybeans in Canada is 1.0. Soybean residues are mainly produced in Ontario and Quebec, accounting for 95.4% of the total Canadian residue from soybean straw. The average soybean straw residue yield (Mg ha^{-1}) from 2001 to 2010 was 2.53 in Ontario (Li et al., 2012). At harvest in 2017, the amount of N provided by the above-ground soybean residues plus below-ground residual N sources (roots + soil) in the microplots was 27 kg N ha^{-1} . The average C/N ratios for the above-ground crop residue and the root material C/N ratios averaged for soybean were 66 and 89, respectively (Taveira et al., 2020). According to the results from Mc Geough et al. 2012, the soybeans grown in Canada typically have the dry matter allocation of soybean, with yield ratio: AG$_{residue}$ ratio: BG$_{residue}$ ratio of 0.30: 0.45: 0.25.

The amount of nitrogen in the soybean seed ranged from 130–170 kg N ha^{-1}, while 11 kg N ha^{-1} was in the straw. Soon and Clayton (2002) reported that the average nitrogen from straw returned to soil was 22 kg N ha^{-1} in northwestern Alberta. In a previous study with no tillage, the nitrogen returned in straw residue was 31–41 kg ha^{-1} and nitrogen returned in root residues was 2–3 kg ha^{-1} (Soon and Arshad, 2002). Therefore, the range of total N inputs from crop residue returned to soil per area (N$_{resi}$/A) is [22, 41] kg N ha^{-1} for this study.

5.1.7. GHG emission coefficient for herbicide usage (*E$_{herb}$*)

Lal (2004) evaluated the carbon emission of herbicide production, transportation, storage, and transfer. The results showed that the GHG emissions range for different pesticides was from 1.70 –12.6 kg C-eq kg^{-1}a.i. with a mean value of 6.3± 2.7 kg CE/kg a.i. which can be converted to the range [6.23, 46.20] kg C-eq kg^{-1} a.i. West and Marland (2002) estimated 4.4 kg CE kg^{-1} a.i. for the production, packaging, and transport of herbicides. According to Lal (2004), the range of equivalent carbon emissions for spraying herbicides, which is one of the farm operations, was

from 0.7 to 2.2 kg C-eq ha^{-1} with a mean value of 1.4± 1.3 kg C-eq ha^{-1}. Thus, the GHG emissions coefficient for herbicide usage (E_{herb}) is in the range of [5.61, 41.60] kg CO$_2$-eq ha^{-1}yr^{-1}, considering 900 g kg^{-1} active ingredient in the pesticide.

5.1.8. GHG emission rate caused by manufacturing, storage, and transportation of N fertilizer (E_{fert_N}) and P Fertilizer (E_{fert_P})

Fertilizer production is a significant source of GHG emissions, contributing to the carbon footprint of agricultural products. Brentrup et al. (2016) reported that urea and calcium ammonium nitrate manufacturing resulted in approximately 2 and 4 kg CO$_2$ kg^{-1} N GHG emission, respectively. Snyder et al. (2009) found that GHG emissions associated with the manufacture and transport of urea, ammonium nitrate, and P$_2$O$_5$ were 3.1, 3.8 and 1.0 kg CO$_2$ kg^{-1}, respectively. The most common N fertilizers (urea and ammonium nitrate) generate 0.84 kg CO$_2$ kg^{-1} N applied (Fixen et al., 2005). Natural Resources Canada (NRCan, 2008) reported on a benchmarking study completed by Plant Surveys International. The study calculated figures for total CO$_2$ emissions from ammonia production. Emissions of CO$_2$ per ton of NH$_3$-N ranged from 2.2 to 2.7 t , with a global average of 2.6 t (Producers, 2008). According to Lal (1998) the production of N fertilizer emits roughly 0.82 kg CO$_2$/kg N GHG emission. West and Marland (2002) reported that GHG emissions from fertilizer production were 0.81 and 0.101 kg CO$_2$ kg^{-1} N and P$_2$O$_5$, respectively. The GHG emissions was estimated to be 1.23 kg CO$_2$ kg^{-1}N by Izaurralde et al. (2019).

The GHG emissions rates of N fertilizer (E_{fert_N}) and P fertilizer (E_{fert_P}) were set at 4.80 kg CO$_2$-eq kg^{-1} N and 0.73 kg CO$_2$-eq kg^{-1} P$_2$O$_5$ in this study (Gan, et al., 2012b). The recommended application amounts for N and P fertilizer are 4 kg N ha^{-1} and 18 kg P$_2$O$_5$ ha^{-1}, respectively. Therefore, the variation range of carbon emission for the production, transportation, storage, and transfer of nitrogen (E_{fert_N}) is [0.9, 1.8] kg C-eq kg^{-1} N, which is [3.30, 6.60] kg CO$_2$-eq kg^{-1} N. Similarly, the range of phosphorus emissions for P fertilizer production, transportation, storage, and transfer (E_{fert_P}) is [1.00×10^{-1}, 3.00×10^{-1}] kg C-eq kg^{-1} P, which converts to [0.37, 1.10] kg CO$_2$-eq kg^{-1} P$_2$O$_5$.

5.1.9. N Fertilizer applied on the farm ($N_{applied}$) and P fertilizer applied on the farm ($P_{applied}$)

Because of its climate and productive farmland, Canada's environmental conditions are favorable for agriculture. Soybeans have provided significant economic opportunities for Canadian farmers. Over time, seed varieties, and fertilizer and pesticide applications have improved, resulting in higher yields. Growers should use a starter fertilizer if soil N levels are low, as shown by fertility tests. However, more than 23 kg of N should never be available within the top 61 cm of soil (Cherian et al., 2016). A large amount of N is removed from the field when soybeans are harvested. This is due to the high protein content of soybean grain (~ 40% or more on a dry weight basis), since protein contains about 16% N. For example, 60 bu of soybean contains ~210 lb N in the grain and ~80 lb N in the above-ground residue, totaling ~290 lb N (Salvagiotti et al., 2008). Soybean begins to move N from the vegetative sections of the plant to the grain around 60 days after planting, or around the R4 growth stage. This suggests that the best time to apply additional nitrogen is before R4 stage (during the early reproductive growth stages) so that fertilizer N is available to the soybean by R4. (Schmidt, 2014).

In a previous study, N fertilizer was applied with the seed at the rate of 2 kg N ha^{-1}yr^{-1} (Meyer-Aurich et al., 2006). Taveira et al. (2020) reported that annual fertilizer N rates for soybean was 8 kg N ha^{-1}. In this study, N fertilizer was applied with the seed at a rate of 4 kg N ha^{-1}yr^{-1}. According to the recommendation from the Ministry of Agriculture, Food and Rural Affairs of Ontario, the application rates of P fertilizer is from 8.7–21.8 kg P ha^{-1}yr^{-1} (Bagg et al., 2017). Therefore, the variation ranges in this study for N fertilizer ($N_{applied}$) and P fertilizer ($P_{applied}$) are [2.0, 8.0] kg N ha^{-1}yr^{-1} and [8.7, 21.8] kg P ha^{-1} yr^{-1}, respectively.

5.1.10. GHG emissions coefficient for farming practices (K_{farm})

Farming practices may contribute to GHG emissions. The GHG emissions from the no-tillage seedbed preparation was predicted to be between 4.0 and 7.1 kg C-eq ha^{-1}(Lal, 2004b). Tillage farming practices (K$_{farm}$) have a GHG emissions coefficient of [15.4, 26.2] kg C-eq ha^{-1}, which is also [56.5, 96.1] kg CO_2-eq ha^{-1}. Holo (Little, 2008) investigated the energy requirement for common cropping systems in eastern Canada. The primary energy consumption was 1.72 GJ ha^{-1} for a no-tillage system on soybean farms and the estimated K$_{farm}$ was 106.5 kg CO_2-eq ha^{-1}.

Therefore, the variation of K_{farm} was set in the range of [56.5, 107.0] kg CO_2-eq ha^{-1} for this study.

Table 15. GHG emissions from farming operations.

Farming oprations	Equivalent carbon emission (kg carbon equivalant ha^{-1})	
	Range	Mean ± S.D.
No-till planting	3.7-3.9	3.8 ± 0.1
Spray herbicide and fertilizer	1.2-3.5	2.3 ± 1.7
Corn harvesting combine	8.5-11.5	10.0 ± 1.5
Plant/Sow/Drill	2.2-3.9	3.2 ± 0.8

Table 16. GHG emission coefficients for tillage, planting, spraying, and harvesting.

Farming operations	Equivalent carbon emission	
	Range (kg carbon equivalant ha^{-1})	Range (kg CO_2- eq ha^{-1})
No-till planting	3.7-7.1	14.7-26.0
Spray herbicide and fertilizer	1.0-3.5	3.7-12.8
Corn harvesting combine	8.5-11.5	31.2-42.2
Plant/Sow/Drill	2.2-3.9	8.1-14.3
Total	15.4-26.2	56.5-96.1

5.2. Factorial analysis

The effects of the various emission parameters, as well as their interactions, were studied using a 2^{11-4} fractional factorial design. Parameters EF_{direct}, EF_{leach}, $FRAC_{leach}$, N_{min}, $N_{resi/A}$, E_{herb}, E_{fert_N}, E_{fert_P}, $N_{applied}$, $P_{applied}$ and K_{farm} were denoted as A, B, C, D, E, F, G, H, J, K and L, respectively (Table 17). Let H = ABCG, J = BCDE, K = ACDF, and L = ABCDEFG be the design generators. A maximum resolution design can be obtained with its defining relation being I = ABCGH = BCDEJ = ACDFK= ABCDEFGL = ADEGHJ = BDFGHK = AFGJL = BEGKL= CEFGHJK = BCFHJL=ACEHKL= CDGJKL = ABDHJKL. A full description of all 11 parameters' aliases relationships is listed in Table 18. The influence of parameter A is represented by [A] in this design. [AB] consists of two effects and is the sum of effect AB and CGH, and so on. A randomized design is shown in Table 19, where the low and high levels are labeled "-1" and "1", according to Yates' order. The signs for multi-factor interactions can be found by multiplying the involved factors. Table 20 shows GHG emissions per area. The maximum GHG emissions is 225.38 kg CO_2-eq ha^{-1} and the minimum emission is 72.00 kg CO_2-eq ha^{-1}.

Table 17. Parameters'aliases

Aliases	Parameter	Range (upper and lower bound)
A	GHG emission coefficient for farming practices (K_{farm})	[56.5, 107.0] kg CO_2-eq ha^{-1} yr^{-1}
B	N Fertilizer applied on the farm ($N_{applied}$)	[2, 8] kg N ha^{-1} yr^{-1}
C	GHG emission rate caused by manufacture, storage and transportation of N fertilizer (E_{fert_N})	[3.3, 6.6] kg CO_2-eq kg^{-1} of N
D	P Fertilizer applied on the farm ($P_{applied}$)	[8.7, 21.8] kg P ha^{-1} yr^{-1}
E	GHG emission rate caused by manufacture, storage and transportation of P fertilizer (E_{fert_P})	[0.37, 1.10] kg CO_2-eq kg^{-1} of P_2O_5
F	GHG emission coefficient for herbicide usage (E_{herb})	[5.61, 41.60] kg CO_2-eq ha^{-1} yr^{-1}
G	Average area N inputs from crop residue to soil (N_{resi}/A)	[22, 41] kg N ha^{-1} yr^{-1}
H	Mineralization N inputs (N_{min})	[0.9, 7.0] kg N ha^{-1} yr^{-1}
J	Emission factor for leaching and runoff (EF_{leach})	[0.0075, 0.0125] kg N_2O-N kg^{-1} N
K	Fraction of N lost by leaching ($FRAC_{leach}$)	[0.05, 0.30]
L	Emission factor from direct emission (EF_{direct})	[0.0016, 0.0102] kg N_2O-N kg^{-1} N

Table 18. Alias relationships for 2^{11-4} fractional factorial analysis

[A] = A	[DK] = DK + ACF	[AFH] = AFH
[B] = B	[DL] = DL + EFH	[AGK] = AGK
[C] = C	[EF] = EF + DHL	[AHJ] = AHJ + DEG
[D] = D	[EG] = EG + BKL	[AHK] = AHK + CEL
[E] = E	[EH] = EH + DFL	[AHL] = AHL + CEK
[F] = F	[EJ] = EJ + BCD	[AJK] = AJK + BEF
[G] = G	[EK] = EK + BGL	[AKL] = AKL + CEH
[H] = H	[EL] = EL + BGK + DFH	[BCF] = BCF + HJL
[J] = J	[FG] = FG + AJL	[BCK] = BCK
[K] = K	[FH] = FH + DEL	[BCL] = BCL + FHJ
[L] = L	[FJ] = FJ + AGL	[BDF] = BDF + GHK
[AB] = AB + CGH	[FK] = FK + ACD	[BDG] = BDG + FHK
[AC] = AC + BGH +	[FL] = FL + AGJ + DEH	[BDH] = BDH + FGK
[AD] = AD + CFK	[GH] = GH + ABC	[BDK] = BDK + FGH
[AE] = AE	[GJ] = GJ + AFL	[BDL] = BDL
[AF] = AF + CDK + GJL	[GK] = GK + BEL	[BEH] = BEH
[AG] = AG + BCH + FJL	[GL] = GL + AFJ + BEK	[BFG] = BFG + DHK
[AH] = AH + BCG	[HJ] = HJ	[BFH] = BFH + CJL +
[AJ] = AJ + FGL	[HK] = HK	[BFL] = BFL + CHJ
[AK] = AK + CDF	[HL] = HL + DEF	[BGJ] = BGJ
[AL] = AL + FGJ	[JK] = JK	[BHJ] = BHJ + CFL
[BC] = BC + AGH + DEJ	[JL] = JL + AFG	[BHK] = BHK + DFG
[BD] = BD + CEJ	[KL] = KL + BEG	[BHL] = BHL + CFJ
[BE] = BE + CDJ + GKL	[ABD] = ABD	[BJL] = BJL + CFH
[BF] = BF	[ABE] = ABE + FJK	[CDG] = CDG + JKL
[BG] = BG + ACH +	[ABF] = ABF + EJK	[CDH] = CDH
[BH] = BH + ACG	[ABJ] = ABJ + EFK	[CDL] = CDL + GJK
[BJ] = BJ + CDE	[ABK] = ABK + EFJ	[CEF] = CEF
[BK] = BK + EGL	[ABL] = ABL	[CEG] = CEG
[BL] = BL + EGK	[ACE] = ACE + HKL	[CFG] = CFG
[CD] = CD + AFK + BEJ	[ACJ] = ACJ	[CGJ] = CGJ + DKL
[CE] = CE + BDJ	[ACL] = ACL + EHK	[CGK] = CGK + DJL
[CF] = CF + ADK	[ADE] = ADE + GHJ	[CGL] = CGL + DJK
[CG] = CG + ABH	[ADG] = ADG + EHJ	[CJK] = CJK + DGL
[CH] = CH + ABG	[ADH] = ADH + EGJ	[DEK] = DEK
[CJ] = CJ + BDE	[ADJ] = ADJ + EGH	[DFJ] = DFJ
[CK] = CK + ADF	[ADL] = ADL	[EFG] = EFG
[CL] = CL	[AEF] = AEF + BJK	[EJL] = EJL
[DE] = DE + BCJ + FHL	[AEG] = AEG + DHJ	[FKL] = FKL
[DF] = DF + ACK + EHL	[AEH] = AEH + CKL +	[GHL] = GHL
[DG] = DG	[AEJ] = AEJ + BFK + DGH	[HJK] = HJK
[DH] = DH + EFL	[AEK] = AEK + BFJ +	
[DJ] = DJ + BCE	[AEL] = AEL + CHK	

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Table 19. The randomized design tables

Run	A	B	C	D	E	F	G	H	J	K	L
1	+1	-1	-1	-1	-1	+1	-1	-1	+1	+1	-1
2	+1	-1	+1	-1	+1	-1	+1	-1	+1	+1	-1
3	-1	+1	+1	-1	-1	-1	+1	-1	+1	-1	+1
4	+1	+1	+1	-1	+1	+1	+1	+1	-1	-1	-1
5	-1	+1	+1	-1	-1	+1	+1	-1	+1	+1	-1
6	-1	+1	-1	+1	-1	-1	+1	+1	+1	-1	+1
7	+1	-1	-1	-1	-1	-1	-1	-1	+1	-1	+1
8	-1	-1	-1	+1	+1	+1	+1	-1	+1	+1	-1
9	-1	-1	-1	-1	+1	-1	+1	-1	-1	+1	-1
10	-1	+1	-1	+1	+1	-1	-1	-1	-1	-1	+1
11	-1	-1	-1	+1	-1	-1	+1	-1	-1	-1	-1
12	-1	-1	-1	+1	-1	-1	-1	+1	-1	-1	+1
13	-1	-1	-1	+1	+1	+1	-1	+1	+1	+1	+1
14	+1	-1	+1	-1	+1	-1	-1	+1	+1	+1	+1
15	+1	+1	-1	+1	+1	+1	-1	+1	-1	-1	+1
16	+1	+1	+1	-1	+1	-1	-1	-1	-1	+1	-1
17	-1	+1	+1	+1	-1	+1	+1	-1	-1	-1	+1
18	-1	-1	+1	+1	-1	+1	-1	-1	+1	-1	+1
19	-1	+1	-1	+1	-1	+1	-1	-1	+1	+1	+1
20	-1	+1	+1	+1	+1	-1	+1	-1	+1	+1	+1
21	+1	+1	-1	+1	-1	-1	-1	+1	+1	+1	+1
22	-1	-1	+1	+1	+1	-1	+1	+1	-1	+1	-1
23	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
24	+1	-1	+1	-1	-1	-1	+1	-1	-1	+1	+1
25	-1	+1	+1	-1	-1	-1	-1	+1	+1	-1	-1
26	+1	+1	-1	-1	+1	-1	+1	-1	+1	-1	-1
27	+1	+1	+1	-1	-1	+1	+1	+1	+1	-1	+1
28	-1	+1	+1	+1	-1	+1	-1	+1	-1	-1	-1
29	+1	+1	-1	-1	-1	+1	+1	-1	-1	+1	-1
30	+1	-1	-1	+1	+1	+1	+1	+1	+1	-1	+1
31	+1	-1	+1	-1	-1	+1	+1	-1	-1	-1	-1
32	-1	+1	+1	+1	+1	+1	+1	-1	+1	-1	-1
33	-1	-1	+1	+1	+1	+1	-1	-1	-1	-1	-1
34	-1	-1	-1	-1	-1	+1	-1	+1	+1	-1	+1
35	-1	-1	+1	-1	+1	-1	+1	+1	+1	-1	+1
36	-1	-1	-1	+1	-1	+1	-1	+1	-1	+1	-1
37	-1	-1	+1	+1	+1	+1	+1	+1	-1	-1	+1
38	-1	-1	-1	-1	-1	-1	+1	-1	+1	+1	+1
39	-1	-1	-1	-1	-1	-1	-1	+1	+1	+1	-1
40	-1	-1	-1	-1	+1	+1	+1	-1	-1	-1	+1
41	+1	-1	-1	+1	-1	+1	+1	+1	-1	-1	-1
42	-1	+1	-1	+1	-1	-1	-1	-1	+1	-1	-1
43	-1	-1	-1	+1	-1	+1	+1	-1	-1	+1	+1

44	-1	+1	-1	-1	-1	-1	+1	+1	-1	+1	-1
45	-1	-1	+1	+1	+1	-1	-1	-1	-1	+1	+1
46	-1	+1	+1	-1	+1	-1	+1	-1	-1	-1	-1
47	+1	-1	-1	+1	-1	-1	-1	-1	-1	+1	-1
48	+1	-1	+1	+1	-1	+1	+1	-1	+1	+1	+1
49	-1	+1	-1	-1	+1	-1	+1	+1	+1	+1	+1
50	+1	-1	-1	+1	+1	-1	+1	+1	+1	+1	-1
51	-1	+1	-1	-1	-1	-1	-1	-1	-1	+1	+1
52	-1	-1	+1	+1	-1	-1	-1	-1	+1	+1	-1
53	+1	-1	-1	-1	+1	-1	-1	-1	-1	-1	-1
54	-1	+1	-1	-1	-1	+1	+1	+1	-1	-1	+1
55	-1	-1	-1	-1	+1	-1	-1	+1	-1	+1	+1
56	+1	+1	-1	+1	+1	+1	+1	-1	-1	-1	-1
57	-1	+1	+1	-1	+1	-1	-1	+1	-1	+1	+1
58	-1	+1	-1	+1	+1	-1	+1	+1	-1	-1	-1
59	-1	+1	-1	-1	-1	+1	-1	-1	-1	-1	-1
60	+1	-1	-1	-1	-1	-1	+1	+1	+1	-1	-1
61	-1	+1	+1	+1	+1	-1	-1	+1	+1	+1	-1
62	+1	+1	+1	+1	-1	-1	-1	-1	-1	-1	-1
63	-1	+1	-1	+1	-1	+1	+1	+1	+1	+1	-1
64	-1	+1	-1	-1	+1	+1	-1	-1	+1	-1	+1
65	+1	+1	-1	-1	+1	-1	-1	+1	+1	-1	+1
66	-1	-1	+1	+1	-1	+1	+1	+1	+1	-1	-1
67	-1	-1	+1	-1	-1	+1	-1	-1	-1	+1	-1
68	+1	-1	+1	-1	+1	+1	+1	-1	+1	-1	+1
69	-1	+1	+1	+1	+1	+1	-1	+1	+1	-1	+1
70	+1	-1	-1	+1	+1	+1	-1	-1	+1	-1	-1
71	-1	+1	+1	+1	-1	-1	-1	+1	-1	+1	+1
72	+1	+1	-1	-1	+1	+1	+1	-1	+1	+1	+1
73	-1	-1	-1	+1	+1	-1	-1	+1	+1	-1	-1
74	+1	+1	+1	-1	+1	+1	-1	-1	-1	-1	+1
75	+1	-1	+1	+1	-1	-1	-1	+1	+1	-1	+1
76	+1	-1	-1	+1	-1	+1	-1	-1	-1	-1	+1
77	+1	+1	+1	+1	-1	+1	+1	+1	-1	+1	-1
78	+1	+1	-1	-1	-1	-1	-1	+1	-1	-1	-1
79	+1	-1	-1	-1	+1	+1	+1	+1	-1	+1	-1
80	-1	+1	+1	-1	+1	+1	+1	-1	-1	+1	+1
81	-1	+1	+1	-1	-1	+1	-1	+1	+1	+1	+1
82	-1	+1	-1	-1	+1	-1	-1	-1	+1	+1	-1
83	-1	+1	+1	-1	-1	-1	+1	+1	-1	-1	-1
84	-1	-1	+1	-1	-1	-1	+1	+1	-1	-1	-1
85	+1	+1	+1	-1	-1	-1	-1	-1	+1	+1	+1
86	+1	+1	+1	+1	+1	-1	-1	+1	+1	+1	-1
87	-1	-1	-1	-1	-1	+1	+1	-1	+1	-1	-1
88	+1	-1	-1	+1	+1	-1	-1	1	+1	+1	+1

89	+1	+1	+1	+1	-1	+1	-1	-1	-1	+1	+1
90	+1	-1	-1	-1	+1	+1	-1	-1	-1	+1	+1
91	+1	+1	-1	+1	-1	-1	+1	-1	+1	+1	-1
92	+1	+1	-1	-1	-1	+1	-1	+1	-1	+1	+1
93	+1	+1	+1	+1	+1	-1	-1	-1	+1	-1	+1
94	+1	+1	-1	+1	-1	+1	-1	+1	+1	-1	-1
95	+1	-1	-1	-1	-1	+1	+1	+1	+1	+1	+1
96	+1	+1	+1	-1	-1	-1	+1	+1	+1	+1	-1
98	-1	-1	+1	-1	+1	-1	-1	-1	+1	-1	-1
99	+1	+1	+1	-1	+1	-1	+1	+1	-1	+1	+1
100	+1	-1	-1	-1	+1	-1	+1	+1	-1	+1	+1
101	+1	+1	-1	-1	-1	-1	+1	-1	-1	-1	+1
102	+1	+1	+1	+1	-1	-1	+1	+1	-1	-1	+1
103	+1	-1	+1	+1	+1	+1	+1	-1	-1	+1	-1
104	+1	+1	-1	+1	+1	-1	-1	+1	-1	+1	-1
105	+1	-1	+1	+1	+1	-1	-1	+1	-1	-1	-1
106	+1	+1	-1	+1	+1	-1	+1	-1	-1	+1	+1
107	+1	+1	+1	+1	+1	+1	-1	-1	+1	+1	-1
108	+1	+1	-1	-1	+1	+1	-1	+1	+1	+1	-1
109	-1	-1	+1	-1	+1	+1	-1	-1	+1	+1	+1
110	-1	+1	-1	+1	+1	+1	-1	-1	-1	+1	-1
111	-1	-1	+1	-1	+1	+1	+1	+1	+1	+1	-1
112	+1	-1	+1	+1	-1	-1	+1	-1	+1	-1	-1
113	-1	-1	-1	+1	+1	-1	+1	-1	+1	-1	+1
114	-1	+1	-1	+1	+1	+1	+1	+1	-1	+1	+1
115	+1	+1	+1	-1	-1	+1	-1	-1	+1	-1	-1
116	+1	-1	+1	+1	-1	+1	-1	+1	+1	+1	-1
117	+1	-1	+1	-1	-1	+1	-1	+1	-1	-1	+1
118	-1	-1	+1	-1	-1	+1	+1	+1	-1	+1	+1
119	-1	+1	+1	+1	-1	-1	+1	-1	-1	+1	-1
120	+1	-1	+1	+1	+1	+1	-1	+1	-1	+1	+1

121	+1	-1	+1	-1	-1	-1	-1	+1	-1	+1	-1
122	+1	-1	+1	-1	+1	+1	-1	+1	+1	-1	-1
123	+1	-1	+1	+1	+1	-1	+1	-1	-1	-1	+1
124	-1	-1	-1	-1	+1	+1	-1	+1	-1	-1	-1
125	+1	-1	-1	+1	-1	-1	+1	+1	-1	+1	+1
126	+1	+1	-1	+1	-1	+1	+1	-1	+1	-1	+1
127	-1	+1	-1	-1	+1	+1	+1	+1	+1	-1	-1
128	-1	-1	+1	+1	-1	-1	+1	+1	+1	+1	+1

The sum of squares for significant factors and interactions are shown in Table 21. The sensitivity of each component and interactions was evaluated by the percentage of contribution of each factor in the table. Factor A, GHG emission coefficient for farming practices (K_{farm}), accounts for 48% of the evaluation. GHG emission coefficient for herbicide usage (Eherb), takes up about 25%. The largest contributor, however, does not always result in the highest GHG emissions. According to the calculations in chapter 4, emissions from agricultural land are higher than emissions from farming operations. N fertilizer applied on farm holds around 17% of contributions. The significance levels of the effects are ranked in Figure 21 from the largest to the smallest effect, and the Pareto chart depicts the absolute values of the standardized effects. K_{farm} was the most significant factors followed by E_{herb}. The GHG emissions of soybean mainly come from the manufacture, storage, delivery, and application of nitrogen. The interaction effect GJ was significantly higher than the main effect of factor K and interaction HK. This indicates a significant interrelationship between factors related to N fertilizer (E_{fertN} and $N_{applied}$).

Figure 22 shows the plot of each main effect. The slope of GHG emission coefficient for farming practices (K_{farm}), N fertilizer applied on the farm ($N_{applied}$), GHG emission rate caused by manufacture, storage, and transportation of N fertilizer (E_{fert_N}), GHG emission coefficient for herbicide usage (E_{herb}), P fertilizer applied on the farm ($P_{applied}$), and GHG emission rate caused by manufacture, storage, and transportation of P fertilizer (E_{fert_P}) are positive. These six factors have a positive effect on GHG emission results. The steeper the slope of each line, the greater the magnitude of the main effect. The GHG emission coefficient for farming practices (K_{farm}) has the

steepest slope, indicating that it has the most influential effect on total GHG emissions. Relatively, mineralization N inputs (N_{min}), emission factor from direct emission (EF_{direct}), emission factor for leaching and runoff (EF_{leach}), fraction of N lost by leaching ($Frac_{leach}$), and total N inputs from crop residue returned to soil (N_{res}/A) are horizontal (parallel to the x-axis). This means that these factors have no significant effects on GHG emission and can be ignored.

An interaction plot was used to show how the value of a second factor affects the relationship between one factor and a continuous response. Figures 5.4 and 5.5 show the interaction relationship between two main effects. For the eleven factors, there are a total of fifty-five (C_{11}^2) interactions. The less parallel the lines are, the more probable it is to be a major interaction.

Figure 23 depicts the correlations between the N fertilizer applied on the farm ($N_{applied}$) and the GHG emission rate caused by the manufacture, storage, and transportation of N fertilizer (E_{fert_N}). With increasing amounts of applied N fertilizer, GHG emissions will increase faster with a high level of GHG emission rate caused by manufacture, and transportation of N fertilizer (E_{fertN}) than with a low level of E_{fertN}. On the other hand, with low levels of applied N fertilizer, GHG emissions are higher at a high quantity of E_{fertN}.

The interaction between P fertilizer applied on a farm ($P_{applied}$) and the GHG emission rate caused by manufacture, storage, and transportation of P fertilizer (E_{fertP}) is shown in Figure 24. When increasing the application amount of P fertilizer, GHG emissions will grow faster with the high level of E_{fertP} than a low level of E_{fertP}. In addition, with the same rate of P fertilizer applied, GHG emissions increase with increasing E_{fertP}. Thus, higher amounts of P fertilizer applied on-farm will result in more GHG emissions. Furthermore, total GHG emissions will rise if the environmental conditions are humid.

Table 20. Variation of the GHG emissions per area.

Factor	Name	Minimum	Maximum	Coded	Values	Mean
A	K_{farm}	56.5	107.0	-1.000=56.50	1.000=107	81.75
B	$N_{applied}$	2	8	-1.000=2.00	1.000=8.00	5.00
C	E_{fert_N}	3.3	6.6	-1.000=3.30	1.000=6.60	4.95
D	$P_{applied}$	8.7	21.8	-1.000=8.70	1.000=21.80	15.25
E	E_{fert_P}	0.37	1.10	-1.000=0.37	1.000=1.10	0.735
F	E_{herb}	5.61	41.60	-1.000=5.61	1.000=41.60	23.60
G	N_{resi}/A	22	41	-1.000=22.00	1.000=41.00	31.50
H	N_{min}	0.9	7.0	-1.000=0.90	1.000=7.00	0.800
J	EF_{leach}	0.0075	0.0125	-1.000=0.0075	1.000=0.0125	0.010
K	$FRAC_{1each}$	0.05	0.30	-1.000=0.05	1.000=0.30	0.175
L	EF_{Direct}	0.0016	0.0160	-1.000=0.0016	1.000=0.0160	0.0088
Y1	Emission	72.00	225.38			

Table 21. Effects of significant factors and interactions

| Source	Sum of squares	Percentage of contribution
L: K_{farm}	1.29×10^{17}	47.78
F: E_{herb}	6.53×10^{16}	24.27
J: $N_{applied}$	4.45×10^{16}	16.53
G: E_{fert-N}	1.37×10^{16}	5.10
H: E_{fert-P}	6.25×10^{15}	2.32
GJ: $E_{fert-N} * N_{applied}$	4.94×10^{15}	1.84
K: $P_{applied}$	4.68×10^{15}	1.74
HK: $E_{fert-P} * P_{applied}$	1.15×10^{15}	0.43
A: EF_{direct}	1014529	3.80×10^{-10}
E: N_{resi}/A	161161	6.10×10^{-11}
C: $FRAC_{leach}$	71761	2.70×10^{-11}
AE: $EF_{direct} * N_{resi}/A$	55960	2.10×10^{-11}
D: N_{min}	16921	6.30×10^{-12}
B: EF_{leach}	8791	3.30×10^{-12}
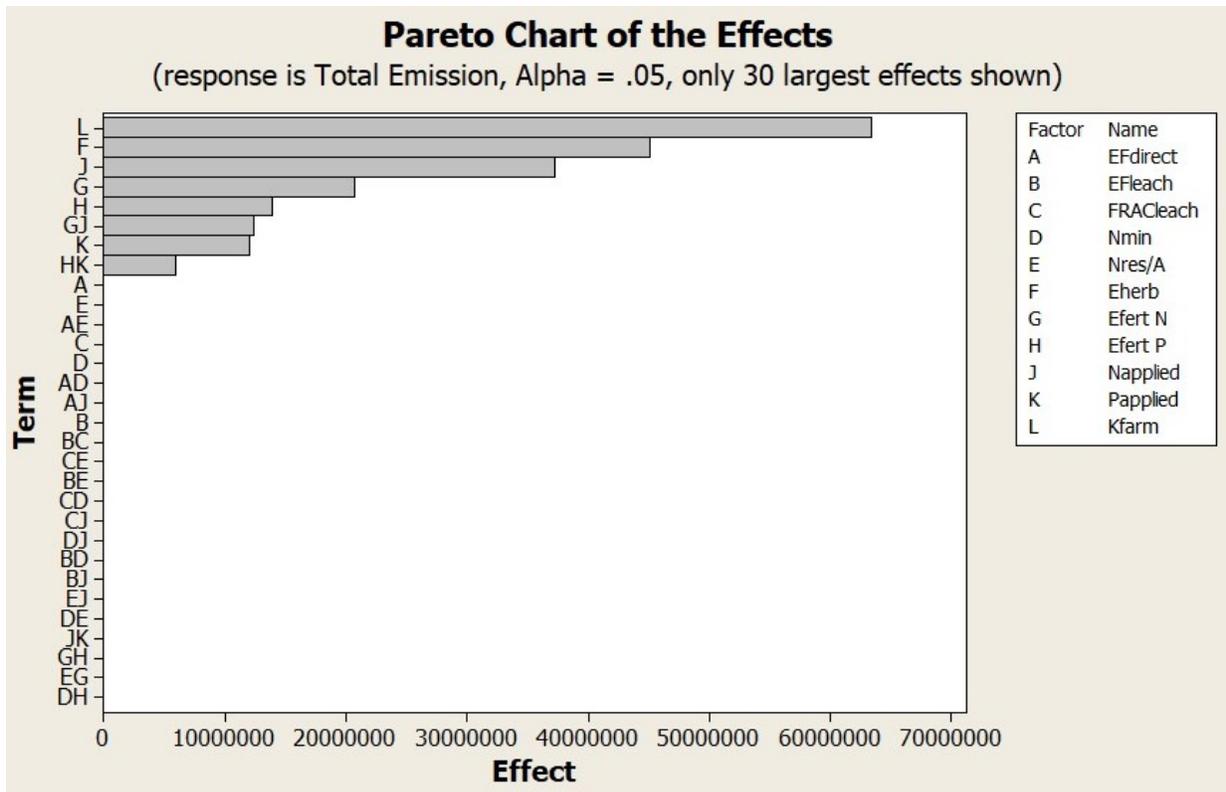
Figure 21. Pareto chart of the effects.
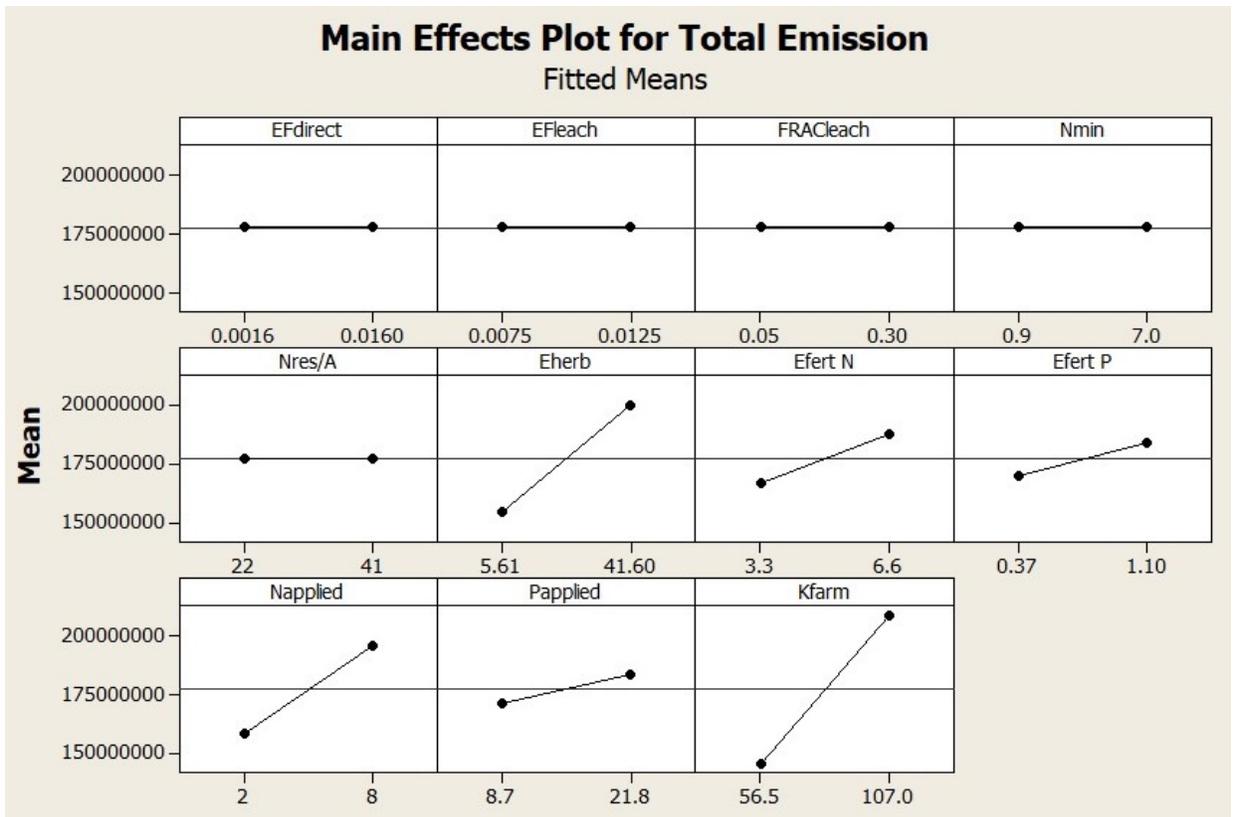
Figure 22. Main effect plots for different factors.
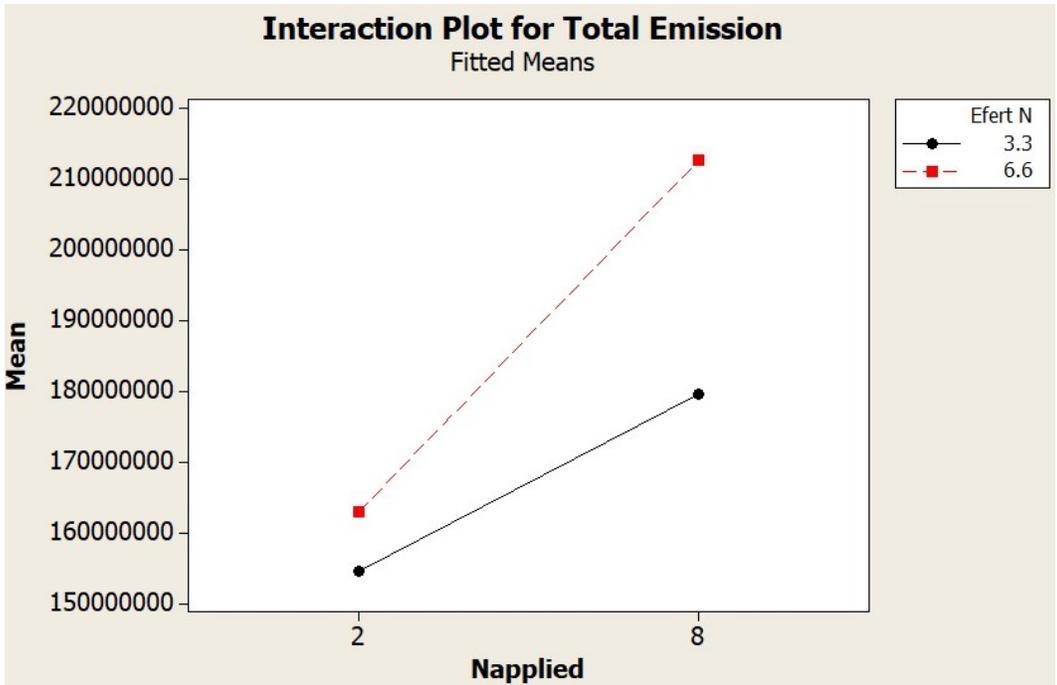
Figure 23. Interaction of GJ
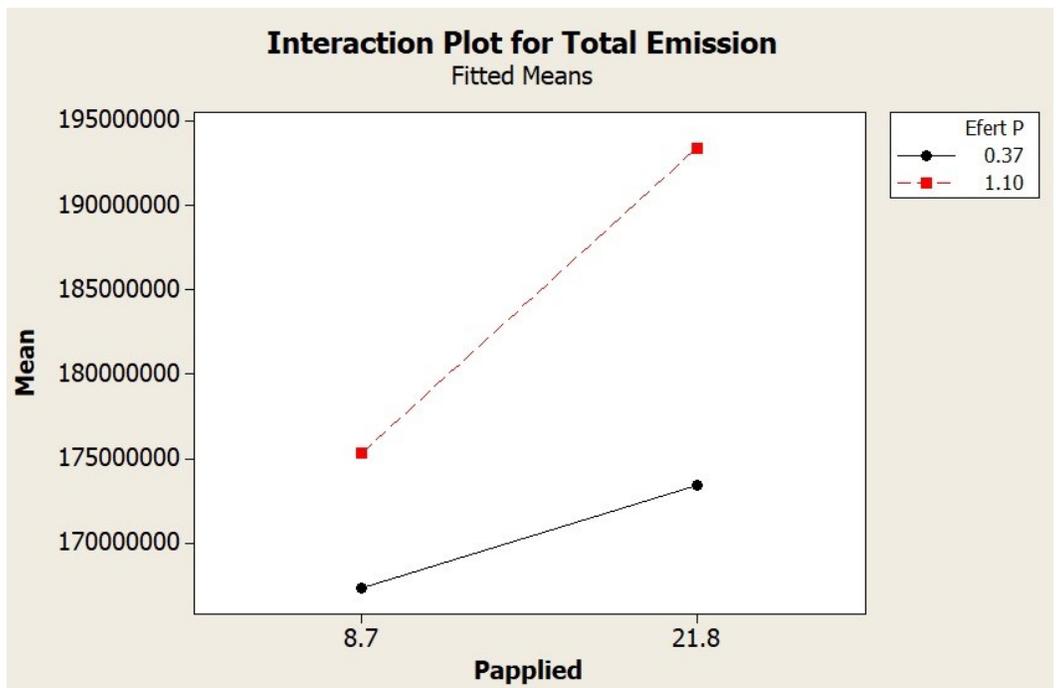
Figure 24. Interaction of HK

Chapter 6. Conclusions

6.1. Conclusions

This study is the first to conduct an assessment of GHG emissions from the soybean cropping system in Ontario. For this research, a general model for evaluating emissions was developed and the main sources of GHG emissions were identified along with, their regional variations. The primary sources included emissions from herbicide usage, emissions from the manufacturing and transportation of N/P fertilizers, emissions from farming operations, and direct and indirect emissions from agricultural lands. A case study based on soybean in Ontario was then investigated. The results reveal that total GHG emissions are mainly caused by agricultural lands; however, environmental conditions also have a major impact on total GHG emissions. GHG_{Ninput} had the highest contribution to total GHG emission among all four emissions in all crop districts and fertilizer N input accounted for the largest portion of GHG_{Ninput} in southern and central Ontario, while in other regions crop residue N input was the largest source. Furthermore, environmental conditions, such as precipitation and evapotranspiration, have a significant impact on the emissions of GHGs such as N_2O. Areas with higher Pr/PE have higher EF_{direct} and total emission. Meanwhile, soybean crops in dry or relatively dry areas have lower amounts of nitrogen returning to the soil from below-ground and above-ground residues than in higher Pr/PE value areas.

The impacts of uncertain parameters were found using multivariate factorial analysis, and the main effects and their interactions were also investigated. The results of the sensitivity analysis demonstrate that the GHG emission coefficient for farming practices (K_{farm}) has the most significant impact on total GHG emissions. When higher rates of N fertilizer were applied, E_{fert-N} would greatly magnify the total GHG emissions.

This research has significant implications for our attempts to assess GHG emissions from agricultural practices and can contribute to efforts to find mitigation possibilities for the sustainable management of agriculture. Using the framework proposed in this research, GHG emissions from the different cropping systems of various regions can also be studied, and the effects of environmental conditions and spatial variations can be assessed.

6.2. Recommendations for future research

The emissions from direct energy (on-farm fossil fuel and electricity use) and indirect energy (the manufacturing of farm inputs, such as synthetic fertilizer) from agriculture must be addressed in the assessment of GHG emissions, even though, these are smaller sources than nitrous oxide and methane. More factors (e.g., soil organic carbon) can be further taken into consideration using multi-year field tests so that GHG emission assessments can be developed further. Also, in-depth exploration of the great influence of irrigation practice emissions, including water pumping and conveyance to optimize irrigation, may provide information that can help to reduce emissions from agricultural lands. Since the fertilizer industry is a consumer of energy and an emitter of CO_2 and other GHGs, it will also be necessary to evaluate GHG emissions during the production of fertilizers.

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