Characterizing Net Life Cycle Greenhouse Gas Emissions and Environmental Performance of Organic Field Crops in Ontario and Quebec

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

The contributions for Chapter 2 are as follows: I, Shenali Madhanaroopan, conducted the analysis and wrote the content, while Dr. Goretty Dias and Dr. Peter Tyedmers provided guidance and revisions.

The contributions for Chapter 3 are as follows: I, Shenali Madhanaroopan, conducted the analysis and wrote the content. Emily Laage, Masters student at Dalhousie University, contributed content to the 'Methods' section. Dr. Goretty Dias and Dr. Peter Tyedmers provided guidance and revisions.

Abstract

Food production systems are at the heart of one of humankind's greatest challenges – meeting the nutritional demands of a population expected to reach 10 billion by 2050 while limiting contributions to environmental degradation and greenhouse gas (GHG) emissions. Thus, producing field crops, which are staple crops for human consumption and animal feed, requires sustainable improvements. Organic farming is often promoted as a climate-friendly alternative to conventional production systems. As a fast-growing agricultural sub-sector in Canada, a robust assessment of the environmental impacts and GHG emissions from organic field crop production systems, considering regionally-specific production conditions and efficiencies, has not been conducted to date.

In this thesis, life cycle assessment (LCA) coupled with modelling soil organic carbon (SOC) changes are utilized to quantify the impact contributions from Eastern Canadian organic wheat, corn, and soybean production to a range of global-scale environmental concerns, including climate change. Specifically, this thesis aimed to characterize the environmental profile of organic field crop production in Eastern Canada, identify the underlying drivers of the impacts, and suggest best management practices for reducing GHG emissions and improving soil carbon stocks in this sector.

LCA results indicate that across all environmental impacts assessed, Eastern Canadian wheat had the largest impact per tonne of crop harvested, followed by corn and soybeans. Net greenhouse gas emissions were 520, 200, and 110 kg CO_2-eq per tonne crop harvested for organic wheat, corn, and soybean production, respectively. Field-level N emissions from nutrient application were the biggest contributor to environmental impacts. Notably, while soil carbon sequestration was observed, it did not result in net negative production emissions. Furthermore, results from a literature review revealed a range of best management practices for enhancing SOC stocks in organic field cropping systems. Practices such as diverse crop rotations with green manure incorporation, less intensive field operations, manure application, and implementing combined practices are suggested to support SOC stocks of organic cropping systems; however, such practices can also contribute to field N emissions if not carefully managed. This work will help LCA researchers, farmers, and organic certification bodies better understand the climate performance of organic systems, while providing a methodological foundation for future organic LCA studies in Canada.

Keywords: Organic agriculture, field crops, greenhouse gas emissions, life cycle assessment, Canada, soil organic carbon, best management practices

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Chapter 1

Introduction

1.1 Background

The global food system is under immense pressure to operate under a changing climate (Challinor et al., 2014), limit its contributions to environmental degradation (Campbell et al., 2017), and sustain the caloric demands of a growing population that is expected to reach 10 billion by 2050 (Ranganathan et al., 2018). However, in pursuit of maximizing yields and reducing production costs, current agricultural production systems are degrading critical resources such as land, freshwater, energy, and nutrients while simultaneously compromising their global regeneration rates (Conijn et al., 2018; Srednicka-Tober et al., 2016). Furthermore, food system activities account for approximately 25% of global greenhouse gas (GHG) emissions (Poore & Nemecek, 2018). To achieve the goals of the Paris Climate Agreement to limit global warming to 1.5°C, substantial reductions in environmental impacts and global GHG emissions within the food production sector are required without compromising the ability to feed a growing world population.

Alternative forms of agriculture, such as organic production, are often promoted as climate-friendly alternatives to conventional production systems. While only 1.5% of global farmlands is managed organically, it remains one of the fastest-growing sub-sectors of the agricultural industry in North America and Europe with one of the most recognized food labels (Seufert & Ramankutty, 2017). For example, organic production in Canada increased 17% from 2019 to 2021 and expansion is expected to increase as the Canadian organic market grows (COTA, 2021). "Certified Organic" agriculture is formally defined as a farming system that prohibits the use of agrochemicals, such as synthetic fertilizers and pesticides, genetically modified organisms, and synthetic compounds used as food additives (IFOAM, 2008); instead, relying on ecologically-based practices and other interventions to enhance yields (McBride et al., 2018). Organic management practices include diverse crop rotations, intercropping, cover cropping, recycling animal manure and crop residues, and green manure growth (Beach et al., 2018). Pest management and weed control is accomplished using strategic cropping techniques, mechanical cultivation, and carefully-managed planting and harvesting dates (El-Shafie, 2020). Thus, in terms of environmental impact, organic production systems are designed to enhance biodiversity and organism abundance, support and maintain soil health and fertility, promote carbon accumulation and storage, recycle plant and animal wastes as nutrients, provide farmers with a livable income, and reduce resource consumption (Leifield, 2012;

Reganold & Wachter, 2016). Management practices and production conditions associated with organic systems are heterogenous, but emphasize increased SOC, improved nutrient cycling, and reduced GHG emissions. However, the environmental and greenhouse gas emission performance of organic cropping systems, especially considering heterogeneous farms under diverse agro-climatic conditions, remains understudied (Bamber et al., 2022; Skinner et al., 2014).

There are many unresolved questions regarding the environmental performance of organic production systems that prompts the need for more research. Some studies have argued that results demonstrating carbon sequestration and climate change mitigation under organic production is premature due to a lack of in-depth and long-term analyses of these systems (Leifeld & Fuhrer, 2010; Khanal, 2009). In addition, yields under organic agriculture tend to be lower than conventional systems, thus requiring more land to produce the same output as a conventional system leading to greater potential for negative environmental impacts (Seufert et al., 2012). However, the environmental performance of organic agriculture is highly dependent on best management practices (Lorenz & Lal, 2023; Gomiero et al., 2011), soil type and characteristics (Skinner et al., 2014), and the climatic regime (Seufert et al., 2012). As a result, research undertaken to characterize the environmental performance of organic management practices in one setting have limited applicability to region-specific production conditions elsewhere (Seufert & Ramankutty, 2017). Thus, robust analyses of organic crop production systems, from a range of agroclimatic and management practices, using primary data, are necessary to understand their environmental impacts, and particularly their GHG performance, especially including soil organic carbon dynamics. Such information may reveal how organic systems, as well as their conventional counterparts, can be improved to meet climate-related goals and better support the natural environment.

Field crop production, such as wheat, maize, rice, soybeans, and barley, grown organically or conventionally, are among the most-produced food commodities worldwide (De Pinto et al., 2020). Canada, in particular, is among one of the major field crop producers, globally (Statistics Canada, 2019). In 2019, field crop production nationally accounted for 21 million hectares of land use and 93.2 million tonnes of production (Statistics Canada, 2019). Organic field crop production is also of particular importance in Canada, occupying approximately one-third of total organic acreage, or 0.53 million hectares (COTA, 2017). In addition, several secondary organic products derived from field crops, such as breakfast cereals, bread, and animal feed are central to the Canadian organic sector (Organic Federation of Canada, 2022). Therefore, assessing the environmental performance of organic field crop production systems, specifically, is essential considering the importance of field crop commodities in Canada and around the world as well as the rate at which organic farming is expanding. Furthermore, a robust analysis of the global warming potential associated with Canadian organic field crop production systems, considering regionally-specific production conditions, has not been conducted to date. In light of Canada's commitments to the Paris Climate Agreement (Government of Canada, 2016) and the Sustainability Productivity Growth for Food Security and Resource Conservation coalition (SPG) following the United Nations Food Systems Summit in 2021 (Agriculture and Agri-Food Canada, 2022), Canada is now, more than ever, in a critical position to accelerate the transition to sustainable food systems. Therefore, an in-depth analysis of Canada's organic field crop sector will help identify the current state of environmental performance, strategies to reduce emissions and improve productivity in the Agri-Food Sector, and reposition Canada as a leader and global competitor in organic field crop production.

1.2 Research Approach and Goals

Agricultural systems are complex; they are dependent on interactions between crops, nutrient application, soil characteristics and type, climate, and management practices. Organic crop production systems, specifically, can be far more heterogeneous in farm size, production practices, yields, and efficiencies than conventional agricultural systems (Keyes et al., 2015). The implications of this heterogeneity for the GHG emissions of Canadian organic field crop production are not well understood. Therefore, to study the environmental performance of food systems, the implications of region-specific conditions on Canadian organic production, and to assess the complexity of GHG dynamics in organic field cropping systems, life cycle assessment (LCA) is a well-suited and frequently applied biophysical accounting method (Cucurachi et al., 2019). LCA is a framework and methodological tool used to quantitatively analyze and model the environmental performance of an industrial product throughout the supply chain (ISO 14044, 2006; Mazzi, 2020; Muralikrishna & Manickam, 2017; Yang et al., 2020). The International Organization for Standardization (ISO) established ISO 14040 and 14044, which define general principles and specific requirements to conduct an LCA (ISO 14044, 2006). An assessment consists of four main steps: 1) goal and scope definition, 2) life cycle inventory (LCI) analysis, 3) life cycle impact assessment (LCIA), and 4) life cycle interpretation (ISO 14044, 2006). The LCI consists of a detailed inventory of material and energy inputs and outputs of production systems. The LCI is then used with one or more impact assessment methods to estimate how these flows contribute to a range of global- to regional-scale renewable and non-renewable resources, human health, and environmental degradation. To date, LCA has been applied frequently as a means of understanding impact contributions arising from an enormous range of food production and associated activities (Poore & Nemecek, 2018, Hoffman et al., 2018; Chiriaco et al., 2017; Williams et al., 2010; Knudsen et al., 2014). Amongst the many insights derived from this research are those associated with understanding how food systems contribute to GHG emissions. Importantly, however, changes in soil organic carbon (SOC) dynamics are scarcely included in crop production LCAs, including those undertaken to characterize impacts of organic agriculture despite the potential impact that changes in SOC may have on net GHG emissions of agricultural production (Almeida-Garcia et al., 2022; Pelletier et al., 2008; Hoffman et al., 2018; Chiriaco et al., 2017; Moudry et al., 2013; Peterson et al., 2013) due to limited site-specific data and consensus on standard methodological approaches.

First, as discussed above, the environmental performance of organic production systems is under-studied, and specifically, there is a lack of knowledge concerning soil organic carbon dynamics and drivers of carbon sequestration potential in organic crop production systems (Leifeld & Fuhrer, 2010). Thus, a review of the literature in Chapter 2 will address the following research question: Which SOC management practices reported for field cropping systems can be applied to the organic agricultural sector to increase carbon stocks and support carbon sequestration, and what are the challenges for applying them? As a result, the objectives of Chapter 2 are as follows:

i) Identify, characterize, and compare a range of SOC management practices that have been reported for organic and conventional field cropping systems; and
ii) Summarize the magnitude of soil carbon stocks resulting from SOC management practices under diverse agro-climatic conditions and field cropping conditions.

Second, Chapter 3 of this thesis employs the LCA methodology coupled with SOC modelling to answer the following question: What are the net life cycle environmental impacts of organic field crop production in Eastern Canada? Given this question, the objectives of Chapter 3 are as follows:

i) Determine the environmental impacts associated with organic field crop production based on regionally-specific production conditions, such as agro-climatic differences and yield, including soil carbon dynamics;

ii) Recommend areas of improvement based on underlying drivers of impacts; and

iii) Understand and convey the implications on future organic LCA studies.

Therefore, the overarching goal is to evaluate the potential of organic field crop production to be a viable solution for reducing the environmental impact from Canada's agricultural production systems and identify best management practices for reducing GHG emissions, both in the organic sector and in conventional production systems where these practices are relevant.

1.3 Thesis Contributions

Mitigating GHG emissions is an international and Canadian priority. Furthermore, productive, climate-friendly, economically viable, and socially just food systems are essential for humankind, the natural environment, and sustainable economic development. Organic production systems and management practices are perceived as having the potential to reduce emissions from the agricultural sector. Therefore, an LCA of organic crop production systems, considering regionally-specific production conditions, will help elucidate the net life cycle environmental implications of organic agriculture in a Canadian context. As a result, this study will build upon existing organic LCA research and contribute rigorous data, a framework for primary data collection methods for agricultural LCAs, and novel methodological knowledge for capturing the complexity and heterogeneity of organic field crop production systems. Furthermore, this research will address the lack of representative estimates of carbon dioxide (CO_2) emissions and the carbon sequestration potential of organic agricultural practices in a Canadian context using Agriculture and Agri-food Canada's whole-farm GHG emissions modelling tool, Holos. As a result, the evaluation of soil carbon dynamics in Canadian organic cropping systems also contributes to the methodological development of future organic LCAs. Taken together, LCA results, soil organic carbon modelling, and a robust evaluation of SOC management practices and stocks will support organic certification bodies and farmers in identifying regional and production system-specific strategies that continue to improve the climate performance of organic agriculture in Canada. Looking ahead, this research will serve as a foundation for continued efforts to assess, evaluate, and improve organic field crop production systems in Canada and similar production and system-specific conditions.

1.4 Thesis Structure

This thesis consists of two main chapters. Following Chapter 1, Chapter 2 presents a systematic literature review examining how management practices employed in agricultural field cropping systems across the northern temperate zone of the globe contribute to soil organic carbon stocks. Chapter 2 describes a range of management practices, summarizes the magnitude of SOC stocks related to agricultural management practices, and provides recommendations to support carbon accumulation and sequestration in organic field cropping systems. Following the literature review, Chapter 3 is a characterization of the GHG emissions and environmental profile of organic wheat, corn, and soybean production in Ontario and Quebec, Canada, using the methodological framework of life cycle assessment coupled with the use of Holos software application to estimate changes in SOC levels and hence, the possible additional emissions or sequestration of CO_2. Chapter 3 includes an environmental impact assessment, the implications and drivers of environmental impacts, and recommendations for improved environmental performance. Chapter 4 will follow with closing remarks regarding overall thesis contributions, implications on the Canadian agricultural sector, and future research directions.

Chapter 2 Literature Review: Supporting Soil Organic Carbon Stocks in Organic Field Cropping Systems

2.1 Abstract

Organic agricultural management is often promoted as a climate-friendly alternative to conventional production systems. To evaluate the potential of organic production systems to contribute to mitigating the climate crisis, it is of great importance to understand how these systems can be more productive and efficient in storing and sequestering carbon. In this review, 89 studies of field cropping systems across the northern temperate zone of the globe are analyzed to 1) identify, characterize, and compare a range of SOC management practices reported for organic and conventional field cropping systems, and 2) summarize the magnitude of SOC stocks under diverse agro-climatic settings, experimental designs, and management practices. In total, 8 broad management practices were identified: tillage treatments, crop residues incorporation, crop rotation diversity and intensification, cover crops, green manure, animal and farmyard manure, reduced fallow, and biochar application. SOC stocks were highly variable across management practices, experimental designs, and regions. Overall, SOC stocks range from 12.1 to 209.0 Mg C ha^{-1}. Higher SOC stocks are related to residue incorporation, crop rotations, reduced tillage, manure application, green manure planting, and a combination of multiple practices. To increase SOC stocks and support long-term carbon sequestration in organic field cropping systems, the following practices are recommended in rank order: no-tillage or reduced tillage in combination with external organic C inputs, high-quality residue producing crops such as maize, diversified cropping rotations that include green manures such as alfalfa, shortened or eliminated fallow periods that are replaced by high quality residue-producing crops, and a combination of management practices that complement site-specific soil conditions to promote soil health, structure, and productivity. These results suggest that as organic field cropping systems become increasingly prevalent, they also have a great capacity to enhance SOC stocks and sequester long-term carbon across the northern temperate zone. Several strategies exist to support SOC of organic field cropping systems effectively and sustainably, but management and their effects can differ depending on site-specific conditions of the system.

Keywords: Soil organic carbon, management practices, organic agriculture, field crops, carbon sequestration

2.2 Introduction

Anthropogenic climate change poses a severe threat to humankind and global biodiversity. Increases in atmospheric CO_2 prompts increased attention and understanding of the Earth's soil organic carbon stocks and their dynamics (Scharlemann et al., 2014; Weismeier et al., 2018). Soil organic carbon (SOC) is carbon derived from decaying vegetation, fungus and bacteria, and the metabolic activity of living organisms (Scharlemann et al., 2014; Gross & Harrison, 2019). Soil carbon is of great importance within the context of rapid environmental change. Carbon stored in the soil has been estimated to be more than three times greater than carbon found in the atmosphere and four times greater than the amount stored in all living plants and animals (Scharlemann et al., 2014). In 2017, over 100 countries contributed to the first global soil map initiative led by the Food and Agricultural Organization (FAO) of the United Nations (UN) (Canadian Society of Soil Science, 2021). Results demonstrate that 680 Gt of soil organic carbon stocks are stored in global top soils (0-30 cm) of which the largest contributors being the Russian Federation (147.9 Gt), Canada (80.2 Gt), and United States of America (54.4 Gt) (Canadian Society of Soil Science, 2021; Deb et al., 2015). Moreover, organic carbon below 30 cm accounts for the majority of global stocks with estimates of 1,505 Gt to soil depths up to 1 m and 3,444 Gt of storage potentially from 0 to 3 m (Canadian Society of Soil Science, 2021). Soils are unique for their incredible ability to store and sequester immense quantities of carbon, especially for hundreds to thousands of years.

Current SOC stocks are threatened by activities such as land use change and management that exacerbate climate change through carbon losses to the atmosphere (Weismeier et al., 2019). In particular, loss of soil C occurs when converting from a previously undisturbed state as grassland or forests to croplands for intensive agricultural activities that accelerate rates of erosion, increase rates of respiration, lower rates of C inputs, and result in poor soil health (Weismeier et al., 2019). Under poor management practices agricultural systems can deteriorate soils and be a net source of C to the atmosphere, but agricultural production systems can also support soils and be a net C sink when managed sustainably and effectively. Furthermore, soil organic carbon plays an influential role in agricultural systems because it forms the basis of soil fertility and works to support nutrient availability for plant growth while promoting soil structure and biological soil health (Deb et al., 2015). In agricultural systems, SOC is managed through soil C inputs, metabolic activity, and supported by crop productivity (Hu et al., 2018). Several studies have assessed the influence of conventionally-managed cropping systems on SOC stocks (Zhao et al., 2013; Benjamin et al., 2010;

Higashi et al., 2014; Gál et al., 2007) and have compared SOC stocks of conventional and organic management systems (Pulleman et al., 2006; Alcántara & Lozano-García, 2014; Leifeld et al., 2009; Venkat, 2012; Hu et al., 2018). Yet, despite its role in regulating soil health and crop productivity, results vary based on factors such as climatic regime, soil type, physical geography, the crops grown, and the management practices used throughout production.

Organic agriculture is often promoted as a climate-friendly alternative to conventional production systems. Despite organic production occupying approximately 1.5% of global agricultural lands, and constituting less than 5% of retail sales, it is one of the fastest-growing sub-sectors of the agri-food industry and the most recognized food label by consumers (Seufert et al., 2017). Organic agriculture is a regulated farming system that prohibits the use of agrochemical inputs such as synthetic chemical fertilizers and pesticides and the cultivation of genetically modified organisms (GMO) (IFOAM, 2008; Gomeiro et al., 2011; Knapp & van der Heijden, 2018). Organic separates itself from systems branded as ‘sustainable’ or ‘agroecological’ due to management practices regulated by national laws (Seufert et al., 2017). Practices used within organic agriculture to address fertility include crop rotations, intercropping, polyculture, cover crops, green manure planting, residue return, and mulching that work to enhance soil fertility and crop productivity. Natural pesticides are often derived from plants; biological control supports pest management, and weed management is often achieved through appropriate crop rotations, seed application timing, and mechanic cultivation, all of which are practices predicated on the ecological environment (Le Campion et al., 2020). As a result, organic agriculture has demonstrated potential benefits such as higher biodiversity and organism abundance, improved soil quality with higher organic carbon contents, improved water quality, and profitability (Leifield, 2012; Reganold & Wachter, 2016). Management practices and production conditions associated with organic systems are heterogenous, but emphasize increased SOC and improved nutrient cycling through growing green manures, planting catch crops, and applying livestock manure, in addition to C inputs from residue management (Hu et al., 2018).While reporting on and comparing SOC management practices between organic and conventional cropping systems provides extensive foundational knowledge, there is also a need to understand, quantify and identify best management practices that support carbon sequestration within organic agricultural systems, specifically as potential tools for climate change adaptation and mitigation.

Organic production systems are an ever-growing sub-sector of agri-food systems with the potential to increase global SOC stocks. Field crop production, such as wheat, corn, rice, soybeans, and barley, grown organically or conventionally, are among the most produced food commodities worldwide (De Pinto et al., 2020). Therefore, the purpose of this literature review is to assess management practices applied to field crop production systems across the temperate region of the globe and arrive at a set of recommendations regarding best management practices for improved carbon stocks and sequestration that can be implemented into organic field cropping systems. This literature review will answer the following question: Which SOC management practices reported for field cropping systems can be applied to the organic agricultural sector to increase carbon stocks and support carbon sequestration, and what are the challenges for applying them?

Given the research question, the literature review will address the following objectives:

iv) Identify, characterize, and compare a range of SOC management practices that have been reported for organic and conventional field cropping systems; and

v) Summarize the magnitude of soil carbon stocks resulting from SOC management practices under diverse agro-climatic conditions and field cropping conditions.

2.3 Methods

2.3.1 Identifying and Selecting Studies for Review

The studies selected for review focused on management practices intended to support soil organic carbon sequestration in organic field cropping systems. Studies were identified in the Scopus database by scanning the titles, abstracts, and keywords of articles using the following search terms:

(“soil organic carbon” OR “soc” OR “organic carbon” OR “soil carbon” OR “organic C”) AND (“management practice*” OR “management” OR “crop management” OR “organic management” OR “soil management” OR “organic amendment*”) AND (“organic farm*” OR “organic cropping system*” OR “cropping system*” OR “organic agricultur*” OR “alternative farm*” OR “alternative agricultur*” OR “ecological farm*” OR “ecological agricultur*” OR “arable farm*”) AND (“crop*” OR “ forage” OR “clover” OR “wheat” OR “oat*” OR “barley” OR “rye” OR “potato*” OR “soybean*” OR “soya” OR “soy” OR “legume*” OR “corn” OR “maize” OR “alfalfa” OR “hay” OR “buckwheat”) AND (“carbon sequestration” OR “c sequestration” OR “soil carbon sequestration”

OR “soil carbon pool*” OR “carbon capture and storage” OR “carbon storage” OR “carbon capture”).

This search yielded 510 results. To identify which papers to include in the review, the following inclusion criteria were applied to yield a final set of studies for the review:

- Studies published between 2011-2021 to reference the most recent literature on this topic and to account for how agricultural processes have evolved in the last decade
- Studies that examine management practices intended to support soil organic carbon
- Studies with a focus on organic agricultural systems and organic management practices
- Studies with an explicit focus on field cropping systems
- Studies with a focus on analyzing the influence of SOC management practices on soil carbon sequestration
- A geographic and climatic scope limited to temperate regions within Canada, the United States, and Europe so that data findings remain relevant to Canadian growing conditions

Titles and abstracts were scanned for their relevance based on the inclusion criteria. A majority of studies reported on research conducted in southern Europe (e.g. Italy and Spain) and Asia (e.g. India), as well as a sizable number from Australia and South America. However, due to geographic and climatic variance, these studies were excluded. In addition, studies were excluded which assessed field crop rotations including rice or other crops not traditionally grown in the US, Canada, and Europe. Due to the scarcity of studies with an explicit focus on assessing SOC dynamics within the context of organic agricultural systems, the inclusion criteria were expanded in three ways. First, studies were included that evaluated conventional agricultural systems that assessed the effects of organic amendments and management practices (e.g. A study assessing use of several synthetic fertilizer treatments including a treatment of farm yard manure on SOC stock or an assessment of conventional tillage compared to conservation tillage and no-tillage). This amendment to the inclusion criteria allows for an assessment of studies that evaluated SOC dynamics within conventional cropping systems that employ frequently applied organic amendments and management practices even if they were not identified as such. Next, the geographic scope was expanded to the northern temperate zone (35°N to 51°N) due to similar climatic environments and crops grown. As a result, field crop studies from north and north-east China were included in this study. Last, the scope was expanded to include relevant studies published in the first few months of 2022. These amendments resulted in a total of 536 studies prior to preliminary screening (Figure 2-1). Following a thorough scan of the database and amendments to the review protocol, the final paper count yielded 89 results.

2.3.2 Data Analysis and Visualization

The selected literature sources were analyzed to organize, summarize, and synthesize reported agronomic practices intended to support soil organic carbon sequestration that are commonly applied in organic field cropping systems. First, information such as types of SOC management practices and their description, how such practices are implemented in the system, associated field crops or their rotation, and the relationship to soil organic carbon sequestration were identified in the source papers, compiled, and presented in the form of a table. This step addresses the first objective of this review, which aims to identify, characterize, and compare a range of SOC management practices that have been reported for organic field cropping systems. Following this, the results were thoroughly analyzed to understand the effects of SOC management practices on the magnitude of soil carbon stocks. Tables were used to presents SOC management practices organized by region, management practice, and reported SOC stock ranges. This step addresses the second objective, which aims to summarize the magnitude of soil carbon stocks as a result of SOC management practices employed under diverse agro-climatic conditions and field cropping conditions. Importantly, studies that published SOC stock magnitudes expressed as Mg C ha^{-1}, t C ha^{-1}, kg C m^{-2} or g C m^{-2} were all converted and presented as Mg C ha^{-1}. In addition, SOC concentrations published in the literature, such as values represented as g kg^{-1}, were also excluded due to missing elements within source papers to convert concentrations to stock (i.e. bulk density and soil depth). Given this criterion, several studies from the review are not included in the SOC stock tables. It is also important to note that in most cases the reviewed literature did not assess management practices in isolation but in combination with other management practices (e.g. Crop rotation – Manure Amendment – No tillage). Therefore, stock values had to be associated with the management practice in question, and when not possible were classified as a “combined management practice”. Furthermore, SOC stock values were sourced from soil depths ranging between 0 and 120 cm deep. However, soil depth variability, among other factors contributing to SOC stock, will be discussed in later sections. Overall, the results will yield a set of recommendations regarding best management practices for improved SOC stocks and carbon sequestration in field cropping systems managed under organic conditions.

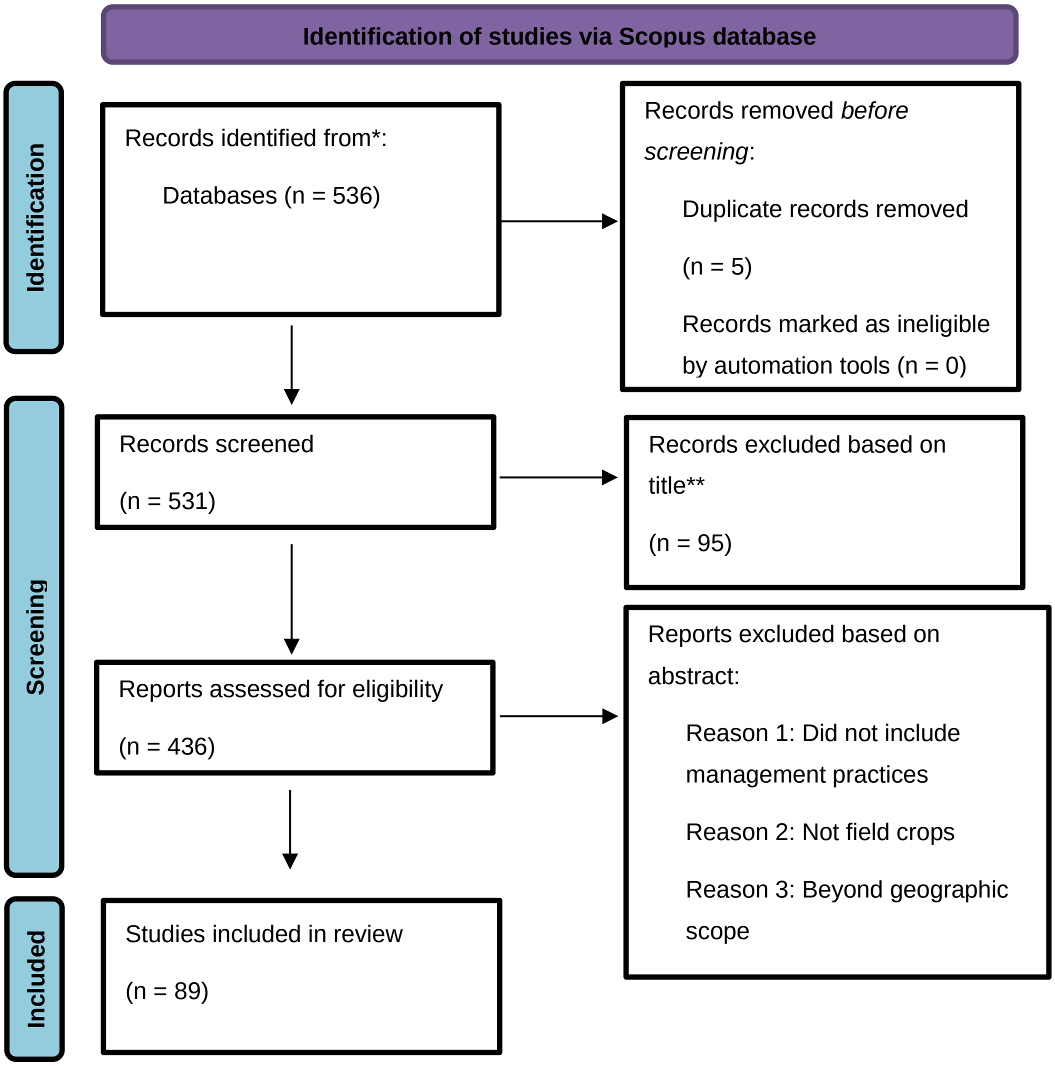


Figure 2-1 PRISMA flow diagram for the identification, screening, and inclusion of studies via Scopus database

2.4 Results

2.4.1 Description of the Studies Assessed

Studies from 12 countries were included in this review. 11% of the studies were from Canada, 15% from Europe, 31% from the United States, and 42% from China (Table 2-1). Study sites ranged in latitude from 35°N to 51°N. This northern temperate zone was reflected in the mean annual temperature, which ranged from 1.1 °C to 13.2 °C (Table 2-1), averaging 7.2 °C. Mean annual precipitation ranged from 320 mm to 1054 mm, with an average of 687 mm. The soil composition of the study sites was variable, and ranged from 6.6 to 56.6% sand, 20.0 to 71.3% silt, and 9.5 to 45.0% clay. A majority of the studies were classified as field experiments (83%), while few assessed SOC changes under simulated conditions (8.6%). Similarly, a small portion of studies conducted both a field site experiment and simulation (8.6%). The duration of most studies was greater than five years and thus, classified as long-term experiments (69%), while the remainder were studies of less than five years and were classified as short-term experiments (31%).

Soil samples were collected at depths ranging from 15 cm up to 120 cm. 9% of studies sampled the soil at depths less than 20 cm, 53% at depths greater than or equal to 20 cm but less than 50 cm, 17% were greater than or equal to 50 cm but less than 100 cm, 16% were greater than or equal to 100 cm, and 6% of studies did not report a soil sample depth.

Field crops were the most common type of crop reported in a study (72%). Only one study assessed impacts associated with legumes (1%), while a sizable portion of studies incorporated both field crops and legumes into their analysis (26%). There was also variation among treatment systems, where 49% of treatments were tested on crop rotations, 17% on monocrop systems, and 23% on studies that assessed impacts on both system types. Among treatment types, a majority of studies investigated the impacts of agronomic management (91%), while few incorporated the influence of land use change as a treatment type (conversion of native land to pasture and pasture to native lands) (9%).

Table 2-1 Descriptive qualities and count from studies assessed

Attribute		Count
Study Location	Canada	8
	United States	22
	Europe	11
	China	30
Study Design	Field Experiment	58
	Simulation/ Model	6
	Both	6
Duration	Long-term (>5 years)	48
	Short-term (<5 years)	22
Soil depth	< 20 cm	6
	>= 20 cm < 50 cm	37
	>= 50 cm < 100 cm	12
	>= 100 cm	11
	NA	4
Crops	Field Crops	49
	Legumes	1
	Both	18
Crop System	Monocrop	12
	Crop rotation	34
	Both	23
Land Management	Land use change	0
	Agronomic Management	63
	Both	6
Annual Precipitation Range (mm)		320-1054
Mean Annual Temperature Range (°C)		1.1-13.2
Soil Composition	Sand (%)	6.6 - 56.6
	Silt (%)	20.0 - 71.3
	Clay (%)	9.5 - 45.0

2.4.2 Characterizing Soil Organic Carbon Management Practices

2.4.2.1 Summary of the Management Practices Identified

The SOC management practices identified were diverse (n=21), with studies assessing single and combined practices (Figure 2-2). In total, 8 broad management practices were identified: tillage treatments, crop residues incorporation, crop rotation diversity and intensification, cover crops, green manure, animal and farmyard manure, reduced fallow, and biochar application. The most commonly examined SOC management practice concerned crop residues (removal and return) (n=33), followed by assessments of crop rotations (n=28), no tillage (n=26), and reduced tillage (or conservation tillage) (n=18) (Figure 2-2). A combination of two management practices were examined most frequently (n=44). The most prominent combination was tillage management and a crop rotation (n=14). The number of studies assessing a single management practices was lower (n=13), with various crop rotations as the most commonly examined practice. The number of studies examining a combination of three management practices was also prominent in the literature (n=26). The most commonly reported combination was tillage management, fertilizer, and a crop rotation (n=10), followed by tillage management, crop rotation, and crop residues (n=8). Table 2-2 identifies, characterizes, and compares the range of SOC management practices discussed in this literature review.

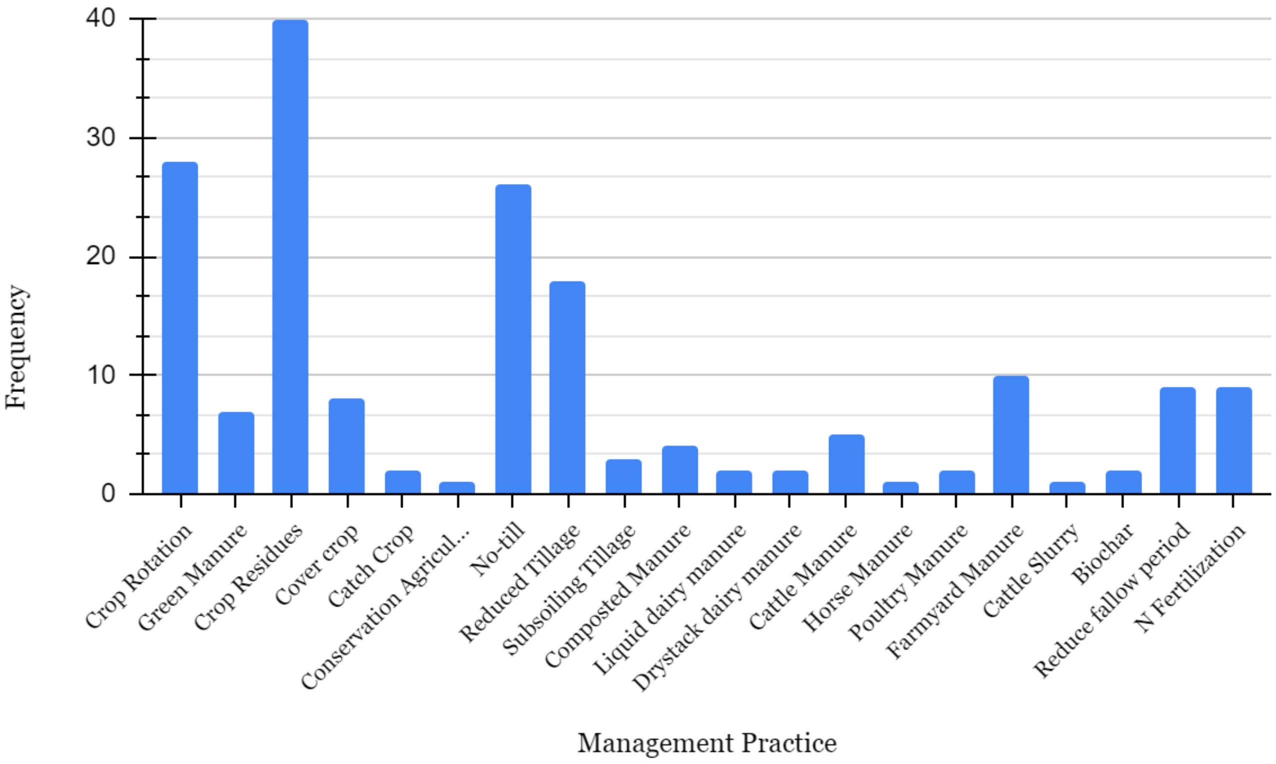


Figure 2-2 The frequency of SOC management practices discussed in 89 agricultural studies published between 2011 to 2022 across 12 countries within the northern temperate zone (35°N to 51°N).

Table 2-2 Identifying the management practices discussed in the literature, which includes the SOC management practice, its description, benefits, limitations, implementation into the system, associated crop(s) or crop rotation (s), potential to sequester carbon, and references

SOC Management Practice	Description	Benefits	Limitations	Implementation into the System	Field crops and/or associated rotation (if applicable)	Potential to Sequester Carbon (Y/N)?	References
No Tillage	Soil is left undisturbed by tillage	SOC enrichment in the surface layer, water conservation, reduce costs and emissions associated with field operations and machinery use	Soil compaction, delayed benefits, C accumulation in the surface only, and variable impacts on yield	Elimination of moldboard plowing, chisel plowing, and disking	Variable (Ex. Corn-Soy rotation)	Y, but C may be constrained to surface layers	a, b, c, d, e, f, g, h, i, j, k, l, m, n, o, p, q, r, s, t, u, v, w, x, y, z
Reduced Tillage	Tillage occurring at a shallower depth	Soil erosion control, water conservation, lower SOC losses, and less soil disturbance	Delayed benefits, manual labour and alternative equipment investments, lower surface soil temperatures caused by surface residues that can lead to reduced yield	Sweep tillage, strip tillage, chisel plowing, skim plowing for superficial cultivation, and altered timing	Cereal crop -legume (Ex. Corn, alfalfa rotation)	Y	d; l; n; r; s; u; w; aa; ab; ac; ad; ae; af; ag; ah
Subsoiling Tillage	Tillage to the subsoil (~40 cm deep)	Deep root growth and SOC storage at depth	High energy requirement and increased costs of production	Tillage to ~40 cm depth using a subsoil shovel	Wheat-corn cropping systems	Y, in combination with no-till	n; ak; al
Crop Reside Retention	Aboveground biomass remaining on cultivated land following a crop harvest	Additional organic amendment, support SOC storage, water and moisture retention, erosion control, conserve soil structure, and crop productivity	Increased likelihood of disease, determining optimal stubble height; Effects can be constrained by temperature and humidity, increased pests, and could lead to carbon emissions	Crop residues can be spread post-harvest and left on the field or incorporated into the soil prior to sowing	Legumes, alfalfa, corn, wheat, and soybean	Y, contingent on residue quantity and quality and in combination with other practices	b; f; i; l; m; n; r; s; u; v; w; x; y; z; ad; ah; ak; al; am; ao; ap; aq; ar; as; at; au; av; ax; ay

Crop Rotation Diversity and Intensification	System of growing different crops in recurring succession on same land	Increased yield, water and nutrient efficiency; reduce N fertilization, disease and pest pressure, and improve weed control; enhance C inputs	C inputs provided by diverse rotations depend on the crop rotated and the quantity and quality of crop residues	Following harvest of a crop, rotate the crop by planting a different crop. Important to consider N use of the crops in a rotation and plant accordingly	Cereals and legumes in rotation are optimal (Wheat-canola-wheat-field pea); Cereal-perennial forage > cereal monoculture	Y, when using high quality residues and legume as cover crop in rotation	d; i; k; m; o; p; r; s; t; w; aa; ab; ac; ah; ai; aj; an; ap; ar; as; az; ba; bb; bc; bd
Cover Crops	Crops seeded between rows for soil support rather than harvest	Soil protection, reduce erosion, increase water infiltration, control weeds, N fixation, and reduce N leaching; Increase crop rotation diversity, microbial activity, and build SOC	Trade-off with agricultural productivity when cash crops are replaced in rotation with cover crop	Sown after main crop is harvested; incorporated by tillage, chemically destroyed, rolled before seeding cash crop, or left on surface to decompose	Hairy vetch, triticale, alfalfa, fescue, red clover, cereal rye, winter wheat	Y, in rotation and combination with no-till for greater biomass production	a; g; k; m; p; ab; ba; bc
Green Manure	Subset of cover crops grown and incorporated into the soil for soil quality	N fixation, disease and erosion control, increased soil aggregation, water infiltration, and deep root growth	Reduced income for farmers during plough-down year	Incorporating green manure plant materials into the soil while still green or immature	Alfalfa, oats, and red clover, soybean	Y, deep root growth distributes C to depth; grow for multiple years	d; e; i; t; ab; ak; az;
Animal Manure & Farmyard Manure	Plant and animal wastes treated as organic soil amendment	C inputs; Recycling and providing essential nutrients for crop growth; Support crop production; Improve soil porosity, infiltration, water holding capacity, soil structure	Manure alone cannot maintain high yields; increased sequestration can be offset by increased N2O emissions	Applied as a basal fertilizer and incorporated using tillage	Variable	Y, direct source of C to the soil, but most effective in combination with crop residues and green manure planting	d; e; ag; ah; aj; ak; am; an; ap; at; av; ax; az; ba; bb; bd; be; bf; bg; bh; bi; bj;

Reduced Fallow Periods	Period when arable land is ploughed and harrowed but left unsown	Re-balance soil nutrient levels; re-establish biota; break crop pest and disease cycles; accumulate and retain water	Limits annual biomass additions leading to reduced C inputs and SOC stocks	Reduce/eliminate fallow period and replace with green manure crop or pulse crop to rebuild SOC	High-quality residue-producing crops (ex. corn or leguminous crop)	N, not a direct correlation, but replacing fallow with C-accumulating practices benefits sequestration	d; i; n; o; ad; ai; ak; an
Biochar Application	Organic amendment derived from pyrolysis of organic materials	Improved soil texture, SOC protection, and retention	Costs to produce large amount of biochar and access facilities for mass production	Applied at a desired rate and either left on surface or incorporated by tillage	Variable	Inconclusive	bj; bo

a)Autret et al. (2016); b) Aziz et al. (2015); c) Bhowmik et al. (2017); d) Brown & Huggins, (2012); e) Dell et al. (2018); f) Gao et al. (2016); g) Gottshall, et al. (2017); h) Grandy et al. (2013); i) He et al. (2021); j) Hirte et al. (2021); k) Huang et al. (2020); l) Jiang et al. (2022); m) Jones et al. (2018); n) Liu et al. (2021); o) Mailliard et al. (2018); p) Schipanski et al. (2017); q) Syswerda et al. (2011); r) Sainju et al. (2014a) s) Sainju et al. (2014b); t) Sanford et al. (2012); u) Stöckle et al. (2012); v) Wu et al. (2017); w) Zhang et al. (2020); x) Zhang et al. (2021); y) Zhang et al. (2022); z) Zhao et al. (2020); aa) Arshad et al. (2011); ab) Cates et al. (2016); ac) Dou et al. (2014); ad) Gollany et al. (2018); ae) Groenigen et al. (2013); af) Krauss et al. (2017); ag) Krauss et al. (2022); ah) Maillard et al. (2016); ai) Romero et al. (2019); aj: Viaud et al. (2011); ak) Li, et al. (2021); al) Zhao et al. (2022); am) Bell et al. (2012); an) Dou et al. (2017); ao) Grandy et al. (2013); ap) Kou et al. (2012); aq) Li et al. (2016); ar) Sainju et al. (2011); as) Weyers et al. (2017); at) Yang et al. (2015); au) You et al. (2017); av) Zhang et al. (2017); aw) Zhang et al. (2018); ax) Zhao et al. (2018); ay) Zhao et al. (2019); az) Blanco-Canqui et al. (2017); ba) Brier et al. (2021); bb) Syp et al. (2012); bc) Wiesmeier et al. (2020); bd) Zhang et al. (2016); be) Kauer et al. (2015); bf) Liu et al. (2017); bg) Xie et al. (2018); bh) Du et al. (2014); bi) Gu et al. (2017); bj) Gross et al. (2022); bk; Liang et al. (2012); bl) Lou et al. (2011); bm) Chang et al. (2020); bn) Katterer et al. (2012); bo; Dong et al. (2018)

Table 2-3 to Table 2-9 presents the range of SOC stocks (Mg C ha^{-1}) related to agricultural management practices for each region under study. SOC stocks were highly variable across management practices and regions. Overall, SOC stocks range from 12.1 to 209.0 Mg C ha^{-1}. Stock ranges that could not be identified in the literature are noted with a hyphen (-) and single values are present where a range was unidentifiable.

2.4.2.2 Tillage Treatments

Tillage treatments such as no tillage (no-till), reduced tillage or conservation tillage, and subsoiling tillage were discussed frequently in the assessed literature. Overall, tillage treatments occurred in 26% of the literature (n=47), with no-till, reduced till or conservation tillage, and subsoiling tillage examined 14% (n=26), 10% (n=18), and 2% (n=3), respectively (Table 2-3).

Table 2-3 SOC stock ranges associated with no tillage, reduced tillage, subsoiling, and conventional tillage (Mg C ha^{-1}), identified from 47 agricultrual studies from sites across the northern temperate zone. SOC stocks are summarized by tillage practices and categorized by four distinct regions (i.e. Canada, Europe, United States, and China).

Management Practice	**SOC stock range by Region (Mg C ha^{-1})**			
	Canada	**Europe**	**United States**	**China**
Tillage				
No Tillage	31.3 – 79.4	94.6	12.1 – 92.5	25.0 – 73.4
Reduced Tillage	46.5 – 80.8	96.4	42.4	24.5 – 92.0
Conventional Tillage	54.2 – 59.1	92.9	12.4 – 83.0	21.0 – 89.0
Subsoiling	–	–	–	52.2 – 91.5

The treatment of no tillage or more commonly, no-till, is an agricultural practice in which the soil is left undisturbed by tillage, which is the practice of preparing the soil for planting and cultivation through mechanical activities (Hirte et al., 2021; Bhowmik et al., 2017). No-till can be implemented into an agricultural cropping system through eliminating moldboard plowing, chisel plowing, disking, or any other commonly known forms of tillage (Hirte et al., 2021). The most commonly examined field crops studied alongside no-till management included continuous cropping systems, such as wheat or barley, double-cropping systems, such as wheat and corn, or more complex rotations consisting of cereal crops and legumes.

Reduced tillage, also referred to as minimum tillage, is a treatment in which tillage occurs at shallower depths of the soil or at a lower frequency compared to conventional systems of ploughing (Zikeli & Gruber, 2017). Similarly, conservation tillage incorporates minimal tillage alongside crop residue retention covering at least 30% of the soil surface (Jiang et al., 2022). Reduced tillage as a management treatment was a commonly examined practice in the assessed literature (n=18). Reduced tillage can be implemented into an agricultural cropping system through sweep tillage, strip tillage, chisel plowing, and skim ploughing for superficial cultivation (Brier et al., 2021; Gollany et al., 2018; Schipanski et al., 2017). Furthermore, reduced tillage can be incorporated through tillage timing that is less intensive than conventional tillage (Zikeli & Gruber, 2017). The most commonly examined field crops studied alongside reduced tillage management were similar to no tillage management. These included continuous cropping systems, field crop rotations, and diverse rotations that included leguminous crops for plow down.

The normal depth of conventional tillage management soil disturbance is typically up to a maximum of 20 cm (Li et al., 2021a). Subsoiling is a tillage management tool that involves tilling deeper into the soil profile to encounter what is referred to as the “subsoil”, typically, at depths up to and beyond 40 cm (Li et al., 2021). Subsoiling was the least discussed form of tillage addressed in the assessed literature (n=3). Subsoiling can be implemented into an agricultural system to depths of approximately 40 cm using a vibrating subsoil shovel after field crop harvest (Zhao et al., 2022). The most commonly examined field crops studied alongside subsoiling tillage management were wheat-corn cropping systems in north and north-east China (n=3).

The range of SOC stocks were identified for no-tillage, reduced tillage, subsoiling, and conventional tillage (Table 2-3). Overall, SOC stocks as a result of no-tillage, reduced, and conventional tillage were variable while the maximum stock due to subsoiling was only reported in China. The maximum SOC stocks for reduced tillage and no tillage are consistently greater than other forms of tillage management across the regions under study. In Canada, the high-end of the SOC stock range was reported from a Quebec-based study from a shallowed soil depth of 0 to 20 cm under a 23-yearlong field experiment of corn managed with reduced tillage and residues left behind (Jiang et al., 2022). In Europe, SOC stock ranges were not available for the tillage practices, but the largest stock was identified from a 4-year crop rotation of corn grain, winter wheat, rapeseed, and winter wheat with a shallow-tillage treatment to a depth of 7 cm (reduced tillage) (Viaud et al., 2011). Next, the greatest SOC stock for reduced tillage in the US simulated SOC stocks and found that four years of reduced tillage yielded 42.4 Mg C ha^{-1} down to 30 cm in the soil profile (Bhowmik et al., 2012). Last, in China, maximum SOC stocks were a result of reduced tillage and returned crop residues (Zhao et al., 2022).

In Canada, the maximum SOC stock under no tillage was reported for a long-term experimental field site down to a soil depth of 20 cm growing continuous corn managed with residues left behind on the soil surface (Jiang et al., 2022). Similarly, in China, maximum stocks were reported from a 30 cm soil profile for continuous corn under no-till management (Zhang et al., 2018). No tillage management in a US-based reported a SOC stock at 92.5 Mg C ha^{-1}, a cumulative stock from 0 to 100 cm from a continuous winter wheat system (Gollany et al., 2018). Interestingly, the maximum SOC stock from conventional tillage system yielded the same value as reduced tillage, but the conventional tillage system underwent greater rates of SOC loss through erosion (0.140 Mg C ha^{-1} yr^{-1} under conventional tillage compared to 0.018 Mg C ha^{-1} yr^{-1}) (Stöckle et al., 2012). The SOC stock for conventional tillage in Europe is significantly higher than minimum stocks across other regions, but it’s important to note the low sample size of European studies reporting tillage management and SOC stocks, as well as functions of soil characteristics (i.e. grain size), climate, and soil history that significantly affect SOC stocks. Viaud et al. (2011) compared no-tillage, shallow tillage, and mouldboard plowing at 0 to 40 cm and reported SOC stocks of 94.6, 96.4, and 92.9 Mg C ha^{-1}, respectively (Table 2-3), demonstrating greater stocks under reduced tillage, but by a marginal difference.

Importantly, SOC stocks differ with soil depth where minimum values of 12.1 and 12.4 Mg C ha^{-1} were reported from studies that evaluated SOC stocks at 0 to 10 cm (Sainju et al., 2014a). The reviewed studies measured SOC stocks at varying soil depths of less than 20 cm and upwards of 100 cm. In some cases, SOC stocks were reported as cumulative stocks across the whole soil profile (i.e. (0-100 cm), while some reported SOC stocks in increments of the total soil profile (i.e. 0-10 cm, 10-20 cm, 20-30 cm, etc.). Expectedly, several studies reported greater SOC stocks and concentrations in the surface of the soil profile (0-20 cm) compared to lower soil depths considering the functions of living material on SOC that largely occur near the soil surface (Maillard et al., 2018; He et al., 2021; Jiang et al., 2022; Syswerda et al., 2011; Cates et al., 2017; Sainju et al., 2014a; Aziz et al., 2015; Sainju et al., 2014b; Dell et al., 2018; Sainju et al., 2011; Stockle et al., 2012; Sanford et al., 2012; Brown & Huggins, 2012; Krauss et al., 2022; Groenugen et al., 2013; Viaud et al., 2011; Krauss et al., 2017; Liu et al., 2021; Zhang et al., 2018; Zhao et al., 2020; Wu et al., 2017). Overall, reducing on-farm tillage demonstrates a greater potential to increase SOC stocks, especially alongside other SOC-enhancing management practices.

2.4.2.3 Crop Residues

Residue-based treatments such as crop residue incorporation were also discussed frequently in the assessed literature. Overall, residue treatments occurred in 22% of the literature (n=40) (Table 2-4).

Table 2-4 SOC stock ranges associated with residue management including returning and removing crop residues (Mg C ha^{-1}) identified from 40 studies from sites across the northern temperate zone. Results are presented by management practice and categorized into four distinct regions (i.e. Canada, Europe, United States, and China).

Management Practice	**SOC stock range by Region (Mg C ha^{-1})**			
	Canada	**Europe**	**United States**	**China**
Residue Management				
Residues Returned	31.3 – 80.8	27.7 – 115.5	-	21.0 – 92.0
Residues Removed	57.0 – 65.2	-	-	16.2 – 82.7

Crop residues refer to above ground biomass (leaves, stalks, roots, and straw) that remain on cultivated land following a crop harvest (Hiel et al., 2018). Crop residues are considered an organic amendment and form of nutrient supply for crop production (Li et al., 2021). Crop residues were the most commonly examined management practice in the assessed literature (n=33). In a tilled system, methods of incorporation include post-harvest spreading of crop residues that are left on the field and then incorporated into the soil (e.g. into the surface 10-20 cm) with a disc and field cultivator prior to sowing (Gao et al., 2016; Li et al., 2021; Jiang et al., 2027). In a no-till system, crop residues are not incorporated and remain on the soil surface (Stöckle et al., 2012). The retained stubble can either be cut high and remain standing or cut low and spread (Gao et al., 2016). Field crops most often discussed in association with residue incorporation were wheat and corn (Li et al., 2021, Chang et al., 2020; He et al., 2021; Jiang et al., 2017).

The range of SOC stock values under residue incorporation were identified for residues returned and removed (Table 2-4). Stock values were unavailable for residues returned in US-based studies, and studies assessing residue removal in Europe and the United States. Nevertheless, SOC stock values are consistently higher under residue return scenarios that scenarios in which residues were removed (Table 2-4). The highest and lowest values under residues returned are 115.5 Mg C ha^{-1} in Europe and 20.1 Mg C ha^{-1} in China, respectively. 115.5 Mg C ha^{-1} was measured down to 70 cm under a fertilized grain-corn system where residues were returned (Katterer et al., 2012). N fertilization may not be the only explanation, but a major contribution to C accumulation due to its impact on above- and below-ground crop residues (Katterer et al. 2012). Likewise, Zhao et al. reported a maximum value of 92.0 Mg C ha^{-1} down to 1-m as a result of returned residues that were tilled into the land to a depth of 10-15 cm (2022).

Conversely, the highest and lowest values of SOC stock due to residue removal are both found in China-based studies at 82.7 Mg C ha^{-1} and 16.2 Mg C ha^{-1}, respectively. 82.7 Mg C ha^{-1} was measured down to 1 meter from winter wheat – summer corn system under the treatment effects of rotary tillage and residues removed (Zhao et al., 2022). Similarly, in Canada, the maximum SOC stock value of 65.2 Mg C ha^{-1} was measured across a 0 to 20 cm soil profile treated with reduced tillage and residues removed (Jiang et al., 2022). Jiang et al. found an increasing trend in the surface 20 cm of the soil profile for all tillage treatments as long as residues were returned, and near constant when residues were removed (2022). Regardless of the combined effects of management practices, SOC stocks seem to increase when residues are returned and decrease when residues are removed.

2.4.2.4 Crop Rotation Diversity and Intensification

Crop rotations as a management practice to support SOC in agricultural systems were examined frequently in the assessed literature (n=28). A crop rotation refers to a system of growing different kinds of crops in recurring succession on the same land, contrary to a monoculture system that grows a single crop continuously on the same land. The range of SOC stock values under cropping intensity were identified for crop rotations and monocrop operations (Table 2-5).

Table 2-5 SOC stock ranges for crop rotations and monocrop systems (Mg C ha^{-1}) identified from 28 studies from sites across the northern temperate zone where results are presented by management practice and categorized by four distinct regions (i.e. Canada, Europe, United States, and China).

Management Practice	**SOC stock range by Region (Mg C ha^{-1})**			
	Canada	**Europe**	**United States**	**China**
Cropping Intensity				
Crop Rotation	32.9 – 209.0	-	13.4 – 128.0	24.0 – 67.0
Monocrop	31.3 – 80.2	-	12.4 – 132.0	21.0 – 73.4

The highest and lowest stock values for crop rotations were identified in Canada at 209.0 Mg C ha^{-1} and the United States at 13.4 Mg C ha^{-1}, respectively. SOC stocks of 209.0 Mg C ha^{-1} were measured from a 0 to 120 cm soil profile on a site managed under an annual crop rotation of oats, soybeans/fava bean, wheat, and flax (Bell et al., 2012). Importantly, this site was managed conventionally. However, under the same crop rotation and soil depth but organic management, SOC stocks were 178.0 Mg C ha^{-1}. Bell et al. attribute the lower C under organic management to no added manure or compost to the organic plots (2012). The second largest SOC stock due to a crop rotation was a simulated result from Jones et al. (2018) reporting 128.0 Mg C ha^{-1} from a corn-soy rotation with rye incorporated. The lowest SOC stock of 13.4 Mg C ha^{-1} were measured from a 0 to 10 cm soil profile under an irrigated no-till malt barley-pea rotation with 67 – 134 kg N/ha (Sainju et al., 2014a). Sainju et al. note that positive C accumulation in the soil surface was attributed to residue production due to N fertilization and no-tillage (2014a). While 13.4 Mg C ha^{-1} is the “lowest” SOC stock for crop rotations, it is important to note that this stock value was identified from a shallower soil depth of 0-10 cm compared to 0 to 120 cm.

The highest and lowest SOC stock values for monocropping were both identified in the United States at 132.0 Mg C ha^{-1} and 12.4 Mg C ha^{-1}, respectively. Jones et al. (2018) reported their highest SOC stocks under perennial cropping (switchgrass and miscanthus) systems (144 Mg C ha^{-1}) compared to their annual system (132.0 Mg C ha^{-1}) of continuous corn with rye double crop. Comparatively, SOC stocks under continuous corn with double cropping and zero residue removal was the best performing annual system with an SOC stock of 132 Mg C ha^{-1} (Jones et al., 2018). While the perennial system had greater SOC levels than the annual system, positive impacts were attributed to the incorporation of rye double crops into their corn-based rotations and the higher percentage of available corn stover (Jones et al., 2018). SOC stocks of 12.4 Mg C ha^{-1} were measured from a 0 to 10 cm soil profile from an irrigated, conventional-till malt barley site with no N fertilization (0 kg N) (Sainju et al., 2014a). Compared with continuous soybeans, corn cropping can supply more organic materials with a slower rate of decomposition leading to greater rates of C accumulation (Kou et al., 2012). Similarly, Zhang et al. (2018) reported a cumulative SOC stock of 73.4 Mg C ha^{-1} from a soil depth of 30 cm under a continuous corn cropping system. In addition, Zhang et al. (2018) found that their continuous cropping system sequestered carbon at a rate of 0.80 Mg C ha^{-1} $year^{-1}$ and attributed these results to contributions from crop residues. While crop rotations and monocropping effectively influenced SOC stocks through factors such as crop residues, it is important to consider cropping pattern, crop type, soil type, additional organic matter amendments, and tillage management that further influence the propensity to store carbon at the surface and at depth.

2.4.2.5 Cover Crops

Cover cropping as a SOC-supporting management practice was not discussed extensively in the literature (n=8), and as a result, a summary of soil carbon stocks related to cover crops, specifically, could not be identified. Cover crops such as hairy vetch, triticale, alfalfa, fescue, red clover, cereal rye, and winter wheat are crops that are seeded between rows for soil support rather than harvest (Autret et al., 2016; Brier et al., 2021; Cates et al., 2017; Gotshall et al., 2017). Cover crops are often implemented into a system through incorporation by tillage, chemically killed, rolled before seeding the cash crop, or left on the soil surface to decompose (Huang et al., 2020; Schipanski et al., 2017; Gotshall et al., 2017; Cates et al., 2017; Autret et al., 2016). In rotation, cover crops are sown after the main crop is harvested at the end of the growing season. Weismeier et al. (2020) identified cover cropping and cover crops as green manure as management practices with great potential for C sequestration (0.18 Tg C $year^{-1}$) due to contributions from above- and belowground residues without compromising crop productivity.

2.4.2.6 Green Manure

Green manure is another management practice addressed in the literature (n=7). Green manure is the practice of incorporating plant materials into the soil while they are still green or immature. Green manures are a subset of cover crops that are grown for the purpose of being turned into the soil and are frequently used to augment soil macro-nutrient, and in particular nitrogen, levels of soils. Green manure crops cited in the literature include alfalfa, oats, and red clover (Blanco-Canqui et al., 2017; Brown and Huggins, 2012; Cates et al., 2016; Dell et al., 2018; Sanford et al., 2012). A range of SOC stock values were also identified for green manure planting and incorporation in Canada and Europe (Table 2-6).

Table 2-6 SOC stocks associated with green manure (e.g. alfalfa and red clover) (Mg C ha^{-1}) incorporation, identified from 7 studies from sites across the northern temperate zone where results are reported from four distinct regions (i.e. Canada, Europe, United States, and Europe).

Management Practice	**SOC stock range by Region (Mg C ha^{-1})**			
	Canada	**Europe**	**United States**	**China**
Organic Amendments				
Green Manure	32.9 – 36.6	60.4 – 72.6	131.9	41.9 – 46.9

The maximum and minimum values among the ranges identified were 131.9 Mg C ha^{-1} in the United States and 32.9 Mg C ha^{-1} in Canada. While a range was not available among studies from the United States, Blanco-Canqui et al. (2018) had the highest reported SOC stock of 131.9 Mg C ha^{-1} down to 100 cm from their 4-year organic system with alfalfa-alfalfa-corn-winter wheat rotation with alfalfa as the green manure. The largest stock from Europe, 72.6 Mg C ha^{-1}, was measured down to 60 cm from a conservation agriculture cropping system of wheat, peas, corn, alfalfa, catch crops, and alfalfa in the rotation as a green manure (Autret et al., 2016). The low end of the range in Europe was 60.4 Mg C ha^{-1}, which was also provided by Autret et al. (2016) and measured from a 0-60 cm soil profile under an organic cropping system of wheat, rapeseed, pea, and alfalfa. Mean annual carbon inputs to the conservation agricultural cropping system was 5.41 t C ha^{-1} year^{-1} while the organic system was only receiving a total of 2.87 t C ha^{-1} year^{-1}, which was a result of greater above-and belowground biomass additions from cover crops (alfalfa and fescue), catch crops, and the main crops in the conservation agriculture system compared to the organic system (Autret et al., 2016). As a result, the mean C sequestration rates of the conservation agriculture system compared to the organic system relative to a conventional system were, 0.55 and 0.20 t C ha^{-1} year^{-1} (Autret et al., 2016). The conservation system performed slightly better due to practices such as no-tillage, permanent soil cover, and a highly diverse crop rotation that contributed substantial crop residue C.

Conversely, 32.9 Mg C ha^{-1} is the lowest of the ranges and was identified from a legume green manure – wheat – wheat rotation (LGM-W-W), and importantly, it was measured from a 0-15 cm soil profile (He et al., 2021). While the highest cumulative C input in this study was from a wheat-canola-wheat-field pea rotation, the LGM-W-W rotation had greater SOC sequestration rates due to higher rates of crop residue C inputs, roots, and root exudates (He et al., 2021). Green manure crops, such as alfalfa, are an effective management practice for subsoil SOC accumulation due to its deep and extensive root growth through the soil profile (Blano-Canqui et al., 2018). These studies have demonstrated that SOC stocks and sequestration rates are positively influenced by factors such as high-quality crop residue C inputs and leguminous green manures incorporated into a rotation.

2.4.2.7 Animal and Farmyard Manure

Manure management practices such as application of cattle (solid and liquid), horse, swine, poultry, farmyard, and composted manure were cited several times in the examined literature (n=27). Manure, in general, is composed of plant and animal wastes, and considered an organic amendment and source of nutrients in agricultural systems. Animal manures are solid, semisolid, and liquid excrements produced by animals that can be applied to agricultural systems. Animal manures, composted manure, and farmyard manure is a mixture of feces, urine, straw, sawdust, waste feed, soil, wash water, crop wastes, and other agro-based litter and by-products. In the studies assessed, manure was often applied as a basal fertilizer at varying application rates and can be incorporated into the soil using tillage (Kou et al., 2012, Chang et al., 2020; Gross et al., 2022; Viaud et al., 2011; Yang et al., 2013). Table 2-7 presents the SOC stocks for animal manure and farmyard manure application to agricultural systems.

Table 2-7 SOC stocks associated with organic amendments including animal manure, farmyard manure (FYM), and composted manure (Mg C ha^{-1}) identified from 27 studies from sites across the northern temperate zone. Results are presented by organic amendment and categorized by four distinct geographic regions (i.e. Canada, Europe, United States, and China).

Management Practice	**SOC stock range by Region (Mg C ha^{-1})**			
	Canada	**Europe**	**United States**	**China**
Organic Amendments				
Animal Manure	77.7	97.7 – 108.7	48.8 – 121.7	27.0 – 45.1
FYM/Composted Manure	184.0 – 190.0	60.7 – 107.8	49	24.0– 43.4

The range of SOC stock values under organic amendments were identified for animal manures (Table 2-7). The highest and lowest SOC stock values identified for animal manure application were 121.7 Mg C ha^{-1} in a US-based study and 27.0 Mg C ha^{-1} in China, respectively. 121.7 Mg C ha^{-1} was measured down to 100 cm from a 4-year organic cropping system of soybean-corn/sorghum-soybean-winter wheat receiving 37 Mg ha^{-1} year^{-1} of cattle manure as an amendment (Blanco-Canqui et al., 2018). In the top 15 cm of their organic system, SOC accumulated at a rate of ~0.16 Mg C ha^{-1} year^{-1} with cattle manure over 40 years (Blanco-Canqui et al., 2018). The second largest SOC stock was reported by Krauss et al. (2022), 108.7 Mg C ha^{-1}, down to 50 cm under reduced tillage and cattle slurry application. Notably, the lowest SOC stock from Europe, 97.7 Mg ha^{-1}, was relatively high, and was measured from a soil depth of 40 cm managed under a 4-year crop rotation of corn grain, winter wheat, rapeseed, and winter wheat amended with poultry manure (Viaud et al., 2011). Conversely, the “lowest” SOC stock among the ranges of animal manure application is 27 Mg C ha^{-1}, which was measured from a 0-20 cm soil profile under a spring corn field amended with both reduced synthetic N and chicken manure applied at a rate of 180 kg N/ha (Chang et al., 2020). Interestingly, the maximum SOC stock reported by Chang et al. (2020) was 33.25 Mg C ha^{-1}, also across a soil profile of 0-20 cm as a result of only organic N applied from manure. Manure application is a rich source of organic carbon, and when combined with minimal tillage operations allows manure to migrate down to deeper soil layers, prevent superficial C accumulation, while maintaining the integrity of the soil.

A range of SOC stock values were identified for farmyard manure application and composted manure in Canada, Europe, and China (Table 2-7). The highest and lowest SOC stocks reported were 190.0 Mg C ha^{-1} in Canada and 24.0 Mg C ha^{-1} in China, respectively. 190.0 Mg C ha^{-1} was measured down to 1-meter from a wheat, barley, and canola cropping system amended with a one-time addition of manure compost and its biochar derivative applied at rates of 7 Mg ha^{-1} each and tilled into the surface 10 cm of the soil (Gross et al., 2022). However, their greatest SOC stock was not too different from the control treatment that measured 184.0 Mg C ha^{-1}. Likewise, Krauss et al. (2017) measured 107.8 Mg C ha^{-1} across a 50 cm soil profile from a treatment of reduced tillage and manure compost (RT-MC) (2017). However, the RT-MC treatment had the greatest SOC accumulation in the surface layer, but depletion in the 20-50 cm layer (Krauss et al., 2017). The lowest value among the ranges, 24.0 Mg C ha^{-1}, was measured from a 20 cm soil profile from a conventional wheat monoculture with basal chemical fertilization plus farmyard manure application (Li et al., 2021). Li et al. (2021) found that farmyard manure application influenced SOC stock increases the most with a great potential for C sequestration, but is more effective when combined with green manure planting, straw return, and manure application.

2.4.2.8 Reduced Fallow Periods

Fallow periods were discussed moderately in the literature and most often in the context of treatment design (n=9). Fallow refers to a period in which arable land is ploughed and harrowed but left unsown. This period of time can range from one to five years before resuming cultivation (OECD, 2001). It is an ancient technique implemented to allow the land to reach balanced levels of nutrients, re-establish biota, break crop pest and disease cycles by removing their host, and accumulate and retain water (Li et al., 2021; Maillard et al., 2018; OECD, 2001). A range of SOC stock values were identified for periods of fallow as a stand-alone treatment or incorporated into a crop rotation (Table 2-8).

Table 2-8 SOC stocks associated with fallow periods (Mg C ha^{-1}) identified from 9 studies across study sites within the northern temperate zone, and results are categorized by four distinct geographic regions (i.e. Canada, Europe, United States, and China), where applicable.

Management Practice	**SOC stock range by Region (Mg C ha^{-1})**			
	Canada	**Europe**	**United States**	**China**
Fallow Periods	31.3 – 46.5	-	55.5 – 65.0	41.7 – 97.5

Data were available for Canada, the United States, and China. The highest and lowest SOC stock values were 97.5 Mg C ha^{-1} in China and 31.3 Mg C ha^{-1} in Canada. 97.5 Mg C ha^{-1} was measured down to 1-meter from continuous farmland fallow (Kou et al., 2012). Importantly, the fallow experiment accumulated the least SOC among the treatments in this study. SOC storage in the 1-meter layer was highest under continuous corn, and followed by a corn-soybean rotation, continuous soybean system, and then fallow. Similarly, 65.0 Mg C ha^{-1} identified in a US-based study measured SOC in the 0-100 cm soil profile from a wheat-fallow experiment under sweep tillage, but found highest SOC stocks under continuous wheat, no-till and a reduced fallow period (Gollany et al., 2018). Likewise, in Canada, maximum SOC stocks related to fallow were measured at 46.5 Mg C ha^{-1} from a 0 to 30 cm soil profile and fallow-wheat with minimum tillage (Maillard et al., 2018). Again, the highest SOC stock measured in the study was 70.07 Mg C ha^{-1} from a continuous wheat system under no-tillage. The lowest value of the SOC stock ranges is 31.3 Mg C ha^{-1}, which was measured from a 0 to 15 cm soil profile under a fallow-high-yielding wheat- high-yielding wheat (F-Hy-Hy) rotation (He et al., 2021). Similar to the larger SOC stocks, this treatment was the lowest of the study. He et al. reports that their wheat-canola-wheat-field pea had the highest cumulative C inputs, and F-Hy-Hy was one of the lowest (2021). As a result, increasing fallow periods and periods of fallow generally result in greater SOC losses.

2.4.2.9 Biochar Application

Biochar as an agricultural amendment was not discussed extensively in the assessed literature (n=2), and as a result, a summary of soil organic carbon stocks could be not identified. Biochar is an organic amendment derived from the pyrolysis of organic materials at a high temperature under low-to-no oxygen conditions (Gross et al., 2022; Dong et al., 2018). For example, Gross et al. (2022) outlines the production of the biochar in their study, which included processing bulk manure compost (composed of alfalfa hay, barley straw, lentil pellets, activated carbon, livestock bedding material consisting of barley and wheat straw, and pine and spruce wood chips to aid in the pyrolysis process) at 650°C for 90 minutes under very minimal oxygen conditions until fully pyrolyzed. Dong et al. (2018) produced their biochar under slow pyrolysis conditions (400°C for 4 hours) using a mixture of organic wastes including rice husks and cotton seed hulls.

2.4.2.10 Combining Management Practices

A sizable number of the studies included in this analysis analyzed and reported the SOC stocks for a combination of management practices within one treatment. Such combinations often included a crop rotation, tillage management, and residue incorporation or an organic amendment, such as manure. Table 2-9 presents SOC stocks as a result of combined management practices from studies across Canada, Europe, the United States, and China.

Table 2-9 SOC stocks associated with combining multiple management practices into one treatment (Mg C ha^{-1}). Ranges are categorized from study sites across four distinct regions of the northern temperate zone (i.e. Canada, Europe, United States, and China).

Management Practice	**SOC stock range by Region (Mg C ha^{-1})**			
	Canada	**Europe**	**United States**	**China**
Combined Practices	75.2 – 102.8	100.3 – 108.7	33.0 – 140.9	25.1 – 115.3

A combination of management practices demonstrated considerable contributions to SOC stocks within a system. The highest and lowest SOC stocks were 140.9 Mg C ha^{-1} from a US-based study and 25.1 Mg C ha^{-1} from China. However, maximum SOC stocks across all regions were very similar. 140.9 Mg C ha^{-1} was measured from a 90 cm soil profile from a high input corn-alfalfa system with reduced tillage, commercial fertilizer, slurry manure, and alfalfa plow-down (Sanford et al., 2012). Notably, Sanford et al. (2012) found a negative correlation between SOC stabilization and tillage, and aboveground C inputs as well as a positive correlation between manure inputs and belowground C inputs when considering the whole soil profile. However, Sanford et al. (2012) conclude that neither manure application nor crop residues alone are sufficient to maintain SOC levels. Next, Kou et al. (2012) reported an SOC stock of 115.3 Mg C ha^{-1}, the maximum stock in China, from a 100 cm soil profile of continuous corn amended with inorganic fertilizer and 23 t ha^{-1}

of organic horse manure. SOC accumulation was attributed to carbon inputs from the horse manure and the plant residues from corn production (Kou et al., 2012). As discussed previously, the maximum SOC stock reported in Europe (0-50 cm) was caused by the combined treatment of reduced tillage and cattle slurry application (Krauss et al., 2017). In Canada, the maximum SOC stock, 102.8 Mg C ha^{-1}, was reported from a 50 cm soil profile under the combined effects of a cereal-perennial forage rotation consisting of barley under-seeded with a forage mixture of orchard grass and red clover, reduced tillage, and liquid dairy manure application (Maillard et al., 2016). Maillard et al. (2016) note that SOC stocks responded positively to long-term dairy manure application in combination with tillage at a reduced frequency (once every three years as opposed to annually) and plant residues from the perennial-based rotation, demonstrating the efficacy of strategically combining management practices to support long-term C accumulation. The lowest reported SOC stock, 25.1 Mg C ha^{-1}, was identified from a shallower soil depth of 20 cm and under the combined effects of a traditional wheat monoculture (without green manure planting during a summer fallow), mineral fertilizer application, with wheat straw return (9 t ha^{-1}), and local farmyard manure application (30 t ha^{-1}). Similarly, in Europe, the lowest SOC stock was identified from a 30 cm soil profile under the combined effects of a continuous corn cropping system with minimum tillage, no manure application, and periods of fallow. Evidently, combining management practices results in significant SOC stocks, but factors such as soil depth, crops grown, tillage frequency, and organic amendments influence its efficacy in accumulating and storing carbon.

2.5 Discussion

The objective of this review is to determine which SOC management practices reported for field cropping systems can be applied to the organic agricultural sector to increase carbon stocks and support carbon sequestration, and identify the challenges for applying these practices. The objectives were achieved by describing a range of management practices that increase SOC, and providing information on the strength of these practices for increasing soil carbon stocks. The practices that consistently resulted in the highest SOC stocks were crop rotation diversity, returning crop residues, reducing tillage, amending the soil with manure, and combining management practices. The practice that resulted in the lowest SOC stocks was periods of fallow.

2.5.1 Improving Crop Rotation Diversity to Increase SOC Stocks

Crop rotation diversity is also an effective management practice due to several reported benefits, which include increased yield, increased water and nutrient use efficiency, reduced N fertilization, disease and pest pressure, and improved weed control (Sainju et al., 2011). Furthermore, several studies note the effects of crop rotations on enhanced organic carbon inputs due to the quantity and quality of deposited crop residues provided by rotating different crops (Blanco-Canqui et al., 2017; Kou et al., 2012; Maillard et al., 2016; Sainju et al., 2011; Wiesmeier et al., 2020; Zhang et al., 2021).

Higher SOC stocks as a result of diverse crop rotations were effectively presented in the literature assessed. He et al. found their wheat-canola-wheat-field pea (W-C-W-P) rotation had the highest cumulative C input, followed by continuous wheat and a legume-wheat-wheat rotation (LGM-W-W) (2021). Compared to average grain crops, canola has higher root/shoot ratios and annual belowground C inputs to a soil depth of 0 to 20 cm were 1.9 to 4.4 times greater than annual grain crops (excluding corn) (He et al., 2021). Furthermore, Weismeier et al. suggests improving crop rotations to benefit SOC stocks by substituting root crops and cereals that can deplete soil organic matter (SOM) with legumes or grass leys that have extensive root systems intended for SOM and SOC gains in agricultural soils (2020). Alfalfa as the green manure in a rotation can lead to SOC gains at 30 to 60 cm depth due to C deposited at greater depths in the soil profile compared with field crops such as corn or soybeans (Dell et al., 2018). Leguminous crops, such as alfalfa, that establish deep roots, supply high quality litter and belowground biomass are recommended in organic field cropping rotations to increase SOC stocks and sequester C. Similarly, Maillard found a 19% higher SOC stock throughout the whole soil profile (0 to 50 cm) in a cereal-perennial forage rotation compared with the cereal monoculture due to the combined benefits of using high-quality residues and legumes as a cover crop in the rotation (2016). In addition, cover crops are a beneficial way to increase crop rotation diversity and provide additional carbon, increase microbial activity, and build SOC due to added above and belowground organic carbon inputs (Autret et al., 2016; Cates et al., 2017; Weismeier et al., 2020). For example, Autret et al. reported mean annual carbon inputs (1998-2014) from fescue and alfalfa at 0.39 and 0.70 t C/ha/year aboveground, respectively, and 0.49 and 0.42 t C/ha/year belowground, respectively (2016). Diversifying a crop rotation can be accomplished in several ways; growing a cover crop, incorporating green manures, and strategically ordering a crop sequence in space and time to support SOC stocks and promote overall soil health.

However, implementing an effective crop rotation can be challenging because it requires knowledge of how and when to arrange one's rotation to meet nutritional yields, as well as investments into certain machinery and operational techniques depending on a crop's needs. In addition, a criticism of growing cover crops or green manures is the possible trade-off of agricultural productivity when cash crops are replaced in rotation with a cover crop (Weismeier et al., 2020). Furthermore, the effects of cropping systems on SOC depend on the agro-climatic setting (precipitation and temperature) as well as the soil structure and composition in which the crops themselves grow, which can determine the crops and type of rotation a farmer can implement effectively (Huang et al., 2020; Sainju et al., 2011; Sainju et al., 2014b; Kou et al., 2012). Therefore, while cropping systems, especially diverse crop rotations, have great potential to support crop yields, accumulate carbon, and sequester carbon, it is important to consider the risks, as well as strategic choices, such as the types of field crops and legumes grown, the pattern of the rotation, and the setting in which the crops are grown to optimize its benefits to agricultural soils.

2.5.2 Returning Crop Residues

Another practice that contributes to high SOC stocks is crop residue return. There are several benefits of crop residue retention, which include being an additional organic amendment to the soil, improving SOC storage, water and moisture retention, soil protection from wind erosion, conserving soil structure, and increasing crop productivity (Gao et al., 2016; Zhang et al., 2021). The practice of crop residue retention is backed by extensive research to support carbon sequestration (Dou et al., 2017, Zhang et al., 2021; Kou et al., 2012; Li et al., 2016; Yang et al., 2013; Yang et al., 2015; He et al., 2021). Studies reported a positive correlation between the magnitude of SOC sequestration and input of organic C derived from crop residues (~97% correlation) (Sainju et al., 2011). Jiang et al (2022) found similar conclusions regarding the positive influence of residue return on SOC stocks. All three residue-return plots experienced improved SOC storage from 1991 to 2013. Over the 23 years of simulation, the highest predicted annual carbon sequestration rate was 0.64 Mg C ha^{-1} yr^{-1} under no-tillage / residues returned (NT-R), followed by 0.55 Mg C ha^{-1} yr^{-1} under reduced tillage – residues returned (RT-R), and 0.54 Mg C ha^{-1} yr^{-1} under conventional tillage – residues returned (CT-R) (Jiang et al., 2022). Furthermore, the quality of residues retained is an important contributor to C sequestration (You et al., 2017). High quality residues like legume biomass and fine roots from alfalfa were found to increase the efficiency of microbial carbon use resulting in more microbial products and greater rates of C sequestration (You et al., 2017). Several studies also highlighted the effects of corn residues as a particular field crop affecting rates of SOC accumulation and C sequestration. (Gao et al., 2016; Zhang et al., 2021; Li et al., 2016; Kou et al., 2012; Dou et al., 2017; Zhang et al., 2020; Yang et al., 2015). Corn residues were found to decompose more slowly than soybean residues due to its high C/N ratio (Zhang et al., 2021; Kou et al., 2012). Li et al. attributed greatest SOC accumulation to their treatment of high corn return and high wheat return (2016). Compared to conventional agricultural practices, combined treatments such as no or reduced tillage and increased cropping intensity can increase surface residues and SOC.

However, challenges related to crop residue retention include the increased likelihood of diseases caused by improper residue management (Gao et al., 2016). In addition, another drawback of crop residue management is N_2O emissions (Jiang et al., 2022; Jiang et al., 2017). Compared with no residues returned under conventional and reduced tillage management, modelling results demonstrated 12-18% greater soil N_2O emissions under residues returned (Jiang et al., 2022). However, combining strategic tillage management to incorporate the residues into the soil profile can reduce nitrate leaching and direct N_2O emissions to the atmosphere, but incorporation has to be well-timed to ensure adequate moisture during drier seasons (Ambus & Jensen, 2001). Nevertheless, plant-derived C is a critical practice supporting the soil and crop productivity, and it is practicable in an organic field cropping system. Under organic crop management, high quality residue-producing crops, such as corn and legumes, are recommended in diverse crop rotations to maximize soil C inputs and long-term C sequestration. To reap further benefits, shortened or eliminated fallow periods that are, instead, replaced with residue-producing crops adds further C inputs to an organic system.

2.5.3 Reducing Tillage

First, reducing tillage is an effective management practice and reported benefits include SOC enrichment in the surface layer due to conserved surface residues and minimal soil disturbance (Cates et al., 2016; Krauss et al., 2017; Maillard et al., 2016). In addition, reducing tillage can conserve soil water more than conventional tillage (Rusu et al., 2014). As a result, crops under reduced management can efficiently use the retained soil water, which can lead to reduced or eliminated periods of summer fallow (Li et al., 2022). Furthermore, reducing or eliminating tillage management can reduce field operation and machinery costs, but may require investments into alternative management practices, especially concerning weed management. Additionally, reducing tillage is associated with reduced carbon emissions due to less diesel consumption (Liu et al., 2021). Importantly, reduced tillage was reported as an effective management practice to support soil carbon sequestration. Reduced tillage can increase soil C sequestration as it prevents soil degradation as a result of reduced soil disturbances (Aziz et al., 2015). In comparison to routine plowing under conventional tillage management, organic material is left to accumulate at the soil surface and decompose at a slower rate (Aziz et al., 2015).

However, eliminating tillage entirely can present some challenges. The practice of no-till management can lead to soil compaction, which results in fewer carbon inputs from crop roots causing the suppression of SOC in sub-surface soil layers (Liu et al., 2021). Furthermore, no-till management can constrain carbon accumulation in the surface layers of the soil and may not always result in C storage throughout the whole soil profile (Autret et al., 2016; Huang et al., 2020). Under no-till management, studies routinely reported a higher distribution of SOC at the surface but decreases as soil depth increased, while the opposite was reported for treatments including tillage (Krauss et al., 2022; Colombi et al., 2019; Viaud et al., 2011). When implementing reduced tillage measures, farmers may experience delayed benefits and variable impacts on yield (Jiang et al., 2022; Liu et al., 2021; Shipanski et al., 2017). In consideration of both the benefits and limitations, reducing tillage is a feasible management practice to implement into organic field cropping systems if adequate resources are accessible to supplement the transition from intensive to reduced tillage management. Thus, it is recommended that reduced tillage occur in combination with organic and conservation agriculture measures such as crop rotations, residue incorporation and green manure management to support C accumulation at depth and C sequestration (Arshad et al., 2011; Jiang et al., 2022).

2.5.4 Improving a Low-Carbon Management Practice

Conversely, the practice that contributes to lower SOC stocks is fallow periods. Fallow periods in a crop rotation were consistently associated with the lowest SOC stocks among treatments assessed in a study (He et al., 2021; Maillard et al., 2018; Liu et al., 2021; Gollany et al., 2018). Although, periods of fallow are still beneficial for water conservation and minimizing production risks in dry condition, this management practice can limit annual biomass additions that can support SOC stocks and increase soil erosion (Gollany et al., 2018). Gollany et al. (2018) found that reducing the fallow period from 15 to 3 months under a system of continuous wheat and no tillage increased

SOC. Li et al. (2021) recommends reducing the fallow period and instead, planting a green manure crop. As a result, final SOC stock, SOC sequestered, and the SOC sequestration rate were higher under all treatments where green manure was planted and incorporated into the summer fallow period (Li et al., 2021). Similarly, Maillard et al. (2018) recommends replacing the period of fallow with pulse crops to rebuild SOC stock after a fallow-wheat rotation. In this study, researchers found higher C inputs from their pulse crops five years after replacing previous wheat-fallow treatments. While C sequestration may not be a direct result of reducing fallow periods, management practices such as planting green manure crops or pulse crops as an alternative to fallow or long periods of fallow have the potential to support SOC stocks and C sequestration long-term. Importantly, replacing a fallow period with a cover or forage crop comes at the cost of additional labour and resources, but amending this practice can sequester additional carbon, conserve the soil and improve soil properties, and support future productivity.

2.5.5 Combining Management Practices

Overall, SOC stocks and sequestration rates of the assessed management practices were variable and demonstrated their effectiveness to different degrees. In this analysis, several studies assessed more than one management practice in a single treatment and reported its effect on SOC changes. Given the guidelines of organic agriculture and the prohibited use of synthetic fertilizers, pesticides, and herbicides, it is recommended that production systems combine the recommended management practices to optimize gains in SOC. For example, organic amendments such as crop residues and manure supply abundant carbon to an agricultural system (Li et al., 2016). Li et al. (2016) found that the largest stock increase from manure application and regarded it as an effective treatment to sequester carbon due the high stabilization of manure-C (2016). In addition, when combined with leguminous crops in a diverse rotation, the system can yield high-quality residues and contributions of C deeper into the soil profile through their extensive root systems. Combining management practices such a leguminous crop in a rotation, amending the soil with manure when needed, reducing the frequency of tillage to support deep incorporation of manure C while maintaining soil integrity, and leaving crop residues behind have proven to be highly effective in accumulating and sequestering carbon in agricultural systems.

Notably, among all the assessed studies, there was great variability in temperature, soil conditions, physical geography, experimental sites and treatments, and lengths of studies (Table 2-1).

As a result, one combination of management practices or a single management practice cannot be prescribed as the optimal mechanism to increase carbon stocks and sequester long-term carbon. However, the management practices discussed and recommended for organic cropping systems can be generally applicable to production systems in the northern temperate zone. Furthermore, management practices that support carbon should be based on system- and site-specific conditions of the organic farm, taking into consideration the available resources, labour, budget, land size, crops, soil type, and climate conditions. Last, it is also recommended that organic farmers test their soil and measure their carbon levels to better understand their farming conditions and the feasibility of management practices to implement into their system to increase or maintain soil carbon levels.

2.5.6 Limitations

However, given these recommendations, it is also important to note the limitations of this review. SOC in agricultural field cropping systems across the northern temperate zone were assessed under varied environmental and experimental conditions. The range in soil depths in which SOC was measured, the number of years an experiment (i.e. limited long-term studies) was analyzed for, agro-climatic differences (i.e. soil characteristics, temperature, precipitation, humidity), and experimental design affects the ability to compare studies on a uniform basis. In addition, few papers provided SOC changes, which is another important indicator of the effectiveness of a management practice, especially under different environmental conditions. Furthermore, the number of studies reporting on management practices and its influence on SOC affects the sample sizes for the reported ranges of SOC stocks. Likewise, given the small sample size, some practices could not be quantified. Last, it is important to note that SOC is not the sole indicator of soil health and the productivity of a system, and so organic producers must consider other indicators such as soil pH, nutrient availability, electrical conductivity, cation exchange capacity, and the presence of beneficial organisms when considering how their farm should be managed (Raghavendra et al., 2020). However, this review provides a robust summary of agricultural management practices in field cropping systems and their influence on soil carbon stocks, thus providing insights into their efficacy and ability to support soil health and crop productivity.

2.6 Conclusion

SOC stocks were highly variable across management practices and regions. Overall, large cumulative SOC stocks were associated with greater crop rotation diversity, with maximum stocks ranging between 67.0 to 209 Mg C ha^{-1}. Crop residue retention also had a considerable effect on SOC stocks with maximum stocks ranging between 80.8 to 115.5 Mg C ha^{-1}. Next, no- and reduced tillage positively influenced SOC stocks with maximum stocks ranging between 73.4 to 94.6 Mg C ha^{-1} and 42.4 to 96.4 Mg C ha^{-1}, respectively. Organic amendments such as livestock manure and compost demonstrated considerable stocks with maximum stocks between 45.1 and 121.7 Mg C ha^{-1} and 43.1 to 190.0 Mg C ha^{-1}, respectively. Last, combining management practices demonstrated the greatest influence on cumulative SOC stocks, which consisted of the combined effects of management practices such as crop rotation diversity, residue incorporation, leguminous crops, and an organic amendment. As a result, maximum stocks ranged between 102.8 and 140.9 Mg C ha^{-1}.

Among all of the studies assessed in this review, several patterns associated with SOC accumulation and management practices were identified. Greater SOC stocks were reported in the surface of the soil profile (0-20 cm), which was attributed to two main causes: tillage treatment and organic C inputs to the soil. Annual SOC changes were consistently higher under residue return scenarios than residue removal scenarios. Next, soil structure and composition play an integral role in the soil’s capacity to store and sequester carbon, and management practices can be used strategically to support soil health and promote increased C gains. Root growth and belowground biomass are key determinants of SOC increases and this can be supported with management practices such as growing green manures and promoting their growth with organic amendments. Last, organic field cropping systems can benefit from a combination of management practices, which was tested numerous times in the literature and recommended throughout this review. Considering the heterogeneity of agricultural production systems due to different climatic regimes, soil conditions, physical geography, and cropping systems, SOC management practices should be combined but incorporated based on the site-specific conditions and needs of the system.

To increase SOC stocks and long-term carbon sequestration in organic field cropping systems, the following practices are recommended: reduced tillage or no tillage in combination with external organic C inputs, high-quality residue-producing crops such as corn, diversified cropping rotations that include green manures like alfalfa, shortened or eliminated fallow periods that are replaced by high quality residue-producing crops, management practices that complement site-specific soil conditions to promote soil health, structure, and productivity, and if possible, a combination of management practices suited for the crops grown and the agro-climatic conditions of the farm. Future research endeavors should explore the relationship between agro-climatic conditions and the efficacy of management practices in storing carbon, as well as changes in soil C, and results relative to initial soil C values to improve the robustness of SOC discussions in an agricultural context. Application of these results could also benefit from future research that recommends management practices based on specific climatic regimes and soil types.

Chapter 3 Characterizing Net Life Cycle Greenhouse Gas Emissions and Environmental Performance of Organic Field Crops in Ontario and Quebec

3.1 Abstract

Sustainably producing staple commodity crops, such as field crops, requires food production systems that can meet the demands of a growing global population while substantially mitigating negative environmental impacts and greenhouse gas emissions. Organic agriculture is often promoted as a climate-friendly alternative to conventional crop production systems. Given the growth of organic farming in Canada and the importance of field crop production in the agricultural sector, this study evaluated the cradle-to-harvest gate environmental performance, with special attention to the climate change potential of Eastern Canadian (Ontario and Quebec) organic wheat, corn, and soybean production using ISO-compliant LCA methodology, supported with production data from individual organic crop producers. The whole-farm greenhouse gas emissions modeling tool, Holos, was also used to determine soil organic carbon changes associated with different management practices. A variety of impact categories were examined, including climate change (long term), fossil and nuclear energy use, freshwater acidification, freshwater eutrophication, land occupation (biodiversity), and water scarcity. The results reveal that across all impact categories included in this analysis, except for land occupation (biodiversity), Eastern Canadian organic wheat had the largest impact per tonne of crop harvested, followed by corn and soybeans. Results were largely driven by field-level N emissions from nutrient application, and while soil organic carbon sequestration was observed under organic wheat, corn, and soybean production, it did not offset all production-related GHG emissions. Management practices such as green manure incorporation, diverse crop rotations, less intensive field operations, and precise application of carbon-rich manure are suggested to improve environmental performance. But, in its current state, the negative environmental burdens of organic field cropping systems in Eastern Canada cannot be overlooked. Further LCA research on organic systems, based on the methodological foundation established in this analysis, can be used to better model environmental impacts of organic systems and establish targeted management practices for emission reductions and carbon sequestration based on region-specific production conditions.

Keywords: Life Cycle Assessment, Organic agriculture, Field crops, Canada, Greenhouse gas emissions, Soil organic carbon, Environmental performance

3.2 Introduction

A primary contributor to the Canadian economy is the agricultural and agri-food sector (Government of Canada, 2021). With approximately 189, 874 farms covering nearly 62.2 million hectares, the Canadian agricultural and agri-food sector is concentrated across the Western Prairies, Quebec, and Southern Ontario (Government of Canada, 2021). Field crop production, such as wheat, corn, rice, soybeans, and barley, grown organically or conventionally, are among the most produced food commodities worldwide as well as staple crops for both human consumption and animal feed (De Pinto et al., 2020; Tabaglio et al., 2015). Canada, in particular, is among one of the major field crop producers, globally (Bamber et al., 2021). Ontario and Quebec, specifically, are major agricultural producers of wheat, corn for grain, and soybeans (Canadian Roundtable for Sustainable Crops, 2017; Statistics Canada, 2019), accounting for approximately 4 million hectares of land between the two provinces (Statistics Canada, 2022). Eastern provinces, specifically, have experienced conversions in area dedicated to pasture and hay land to annual cropping systems, such as field crop farms (Liu et al., 2020). As a result, current use of these lands results in environmental degradation, such as soil loss (Liu et al., 2020), energy and water consumption (Dyer & Desjardins, 2016), and increases in GHG emissions (Agriculture and Agri-Food Canada, 2016; He et al., 2018) that exacerbate the negative effects of agriculture on the environment and climate change (Challinor et al., 2014). Such issues must be addressed to ensure Canada can meet its goals to limit global warming to 1.5 to 2°C. Therefore, as field crop production expands across Ontario and Quebec, Canada is now, more than ever, in a critical position to implement best management practices to reduce emissions, improve agricultural efficiencies, and accelerate the transition to sustainable food systems.

Organic production is often promoted as the paradigm for sustainable agriculture and food security. Globally, in 2019, 72.3 million hectares of land was reportedly occupied by organic agriculture, including areas in-conversion (FiBL, 2021). In Ontario and Quebec, there are a reported 567 and 926 organic producers as of 2021, respectively, representing 25% of certified organic producers in Canada (COTA, 2021). The growth and popularity of organic production is not unprecedented given recent emphasis on environmental protection measures, increased consumer demand and consumption, and several cited benefits of organic farming, such as higher biodiversity, improved soil and water quality, enhanced profitability, and greater energy efficiency (Seufert & Ramankutty, 2017; MacRae et al., 2010). However, its environmental performance remains inconclusive considering organic production systems are managed heterogeneously and their performance can be highly context-dependent (Lorenz & Lal, 2023; Gomiero et al., 2011; Skinner et al., 2014; Seufert et al., 2012; Viana et al., 2022). Consequently, estimates of average performance based on data complied from different locations have limited applicability to region-specific production conditions (Seufert & Ramankutty, 2017). Therefore, despite wide-spread expansion and international and national regulations, a robust assessment of the net environmental impacts from Canadian organic field crop production has not yet considered regionally-specific production conditions and efficiencies, and specifically using life cycle assessment (LCA) research, remains under-studied (Bamber et al., 2021).

Given the scale and growth of Eastern Canadian organic field crop production and heterogeneity in yields, management practices, efficiencies, and production conditions, such implications on environmental performance will be assessed using the methodological framework of environmental Life Cycle Assessment. LCA is a framework and methodological tool of life cycle thinking used to quantitatively analyze and model the environmental performance of an industrial product throughout the supply chain (ISO 14044, 2006; Mazzi, 2020; Muralikrishna & Manickam, 2017; Yang et al., 2020), and is a well-suited and frequently applied research method to study agricultural systems (Cucurachi et al., 2019). In this Chapter, LCA methodology, with supporting models for estimating emissions and soil organic carbon will be employed to characterize and quantify the environmental impacts associated with organic wheat, corn, and soybean production across Ontario and Quebec. This research will utilize current organic agricultural LCA knowledge and methodology, identify how to reduce impacts in these systems, and provide insights on how to meet climate-related goals and reduce GHG emissions to better support farmers and the natural environment.

3.2.1 Literature Review

The following literature review covers the methodological aspects of organic agricultural LCAs, findings from organic LCA studies, soil organic carbon in organic LCAs, and recommendations for reducing environmental impacts.

3.2.1.1 Methodological Aspects of Organic Agricultural LCAs

Although LCA had been used extensively to determine the environmental impacts of conventional crops, such as soybeans (Mohammadi et al., 2013), wheat (Charles et al., 2006; Anne-

Grete et al., 2012), wheat-corn rotations (Wang et al., 2014), barley, and oat (Anne-Grete et al., 2012), it has not been applied to the same degree to analyze the performance of crops produced under organic management. Some of the earliest studies were on potential emission reductions from a transition to organic production of four major field crops in Canada (Pelletier et al., 2008), organic swine (Halberg et al., 2010) and poultry production systems (Boggia et al., 2010), as well as organic dairy production (Cederberg & Stadig, 2003; Schader et al., 2014). More recently, LCA has been used to compare the performance of organic and conventional production systems based on environmental indicators, quantifying GHG emissions and energy use (Hoffman et al., 2018; Chiriaco et al., 2017; Williams et al., 2010; Cooper & Leifert, 2011; Knudsen et al., 2014), identifying 'hotspots' of environmental impacts and best management practices for improved cultivation (Hoffman et al., 2018; Chiriaco et al., 2017; Williams et al., 2010; Verdi et al., 2022; Coppola et al., 2022; Keyes et al., 2015), and proposing mitigation strategies concerning efficiency and environment protection (Hoffman et al., 2018; Verdi et al., 2022; Coppola et al., 2022; Venkat, 2012).

Common issues in an agricultural LCA, regardless of the management system, is the choice of a unit of analysis to compare impacts (i.e. the functional unit). The most common basis of analysis is a mass-based functional unit, such as impacts expressed per 1kg or 1t harvested crop or finished product (e.g. bread, pasta, etc.) (Almeida-Garcia et al., 2022; Bacenetti et al., 2016; Liang et al., 2017; Meisterling et al., 2009; Pelletier et al., 2008; Venkat, 2012; Williams et al., 2010; Zingale et al., 2022). However, in some studies, LCA results are expressed on an area-based functional unit, such as impacts expressed per hectare (Gao et al., 2022; Dheri et al., 2022; Hoffman et al., 2018; Hu et al., 2018). Specifically, a hectare-based functional unit is more commonly used in LCA studies of organic farming systems based on the argument that organic systems may demonstrate higher impacts per unit of product due to lower yields per unit area compared to conventional agricultural systems (van der Werf et al., 2020). However, from a standardized LCA perspective, the functional unit must be chosen based on the 'function' of the system (van der Werf et al., 2020; Schau & Fet, 2007) and expressing results per hectare does not accurately represent or reflect the broader functions of agricultural systems.

Most often, the boundary of analysis in both organic and conventional agricultural LCAs is 'cradle-to-farmgate', which includes activities during the agricultural phase, such as field operations and their associated energy inputs and emissions, nutrient application, as well as emissions associated with upstream activities, including the production of fertilizers, soil amendments, seeds, and pesticides, production and maintenance of farm machinery and infrastructure, and transportation of inputs to the farm (Boone et al., 2019; Goglio et al., 2018; Hoffman et al., 2018; Knudsen et al., 2014; Rebolledo-Levia et al., 2022; Almeida-Garcia et al., 2022; Gao et al., 2022; Liang et al., 2017; Kamali et al., 2017). Within these boundaries, the greatest contribution to Global Warming Potential (GWP) associated with field crop production is related to field-level emissions of N compounds and manure application. Therefore, field-level emissions and organic N application can be considered as underlying drivers of environmental impacts within organic production systems, which prompts further analysis into understanding its magnitude and strategies to mitigate its impact.

A few studies have conducted a cradle-to-retail gate LCA, which includes processing, packaging, and transportation past the farm gate (Chiriaco et al., 2017 & Moudry et al., 2013). These studies identified agricultural crop production as the 'hotspot' throughout the product's life cycle (Moudry et al., 2013 & Chiriaco et al. 2017). Specifically, Chiriaco et al. (2017) conducted an LCA of wholemeal bread from cradle-to-retail gate and found the agricultural production of organic wheat contributed the greatest proportion of GHG emissions (63%) in the lifecycle.

A major challenge for any agricultural LCA is data availability. Data to build the background life cycle inventory and conduct the analysis are collected from a variety of sources, which includes databases such as 'ecoinvent' (leading LCI database) (Nemecek et al., 2011; Hoffman et al., 2018; Rebolledo-Levia et al., 2022; Chiriaco et al., 2017), census and statistical data (Pelletier et al., 2008), published values (Pelletier et al., 2008; Nemecek et al., 2011; Knudsen et al., 2014), and primary data collection through field experiments (Hoffman et al., 2018; Knudsen et al., 2014), surveys administered to farmers (Fedele et al., 2014; Rebolledo-Levia et al., 2022; Tricase et al., 2018;) and interviews with farm managers, agronomists, and experts in the field (Tricase et al., 2018; Chiriaco et al., 2017). Although readily available data makes it easier to conduct an LCA, it may not be representative of farm-level environments, such as soil and climate conditions, land management practices, and crop yields that are specific to each system. Specific data, such as historical on-farm records and current production data from farmers are best suited for determining resource use and emissions, while published and publicly available data can be used to determine upstream and post-farm gate impacts. Therefore, it is crucial to choose appropriate data collection methods depending on the goal of the LCA.

Most of the current applications of LCA in organic food systems have only quantified the GWP (expressed as CO_2 equivalents) (Chiriaco et al., 2017; Gao et al., 2022; Knudsen et al., 2014; Liang et al., 2017) or GWP and energy use (Hoffman et al., 2018; Guareschi et al., 2019). Global Warming Potential is a commonly used metric to normalize the impact of different GHG emissions to a common unit, and a widely accepted reference measure in LCAs. However, as more quantitative studies have become available on emissions and impacts of organic production, more impact categories are being analyzed, such as contributions to ozone depletion (Gonzales-Garcia et al., 2021: Rebolledo-Levia et al., 2022; Pelletier et al., 2008; Fedele et al., 2014), terrestrial and freshwater ecotoxicity (Rebolledo-Levia et al., 2022; Gonzales-Garcia et al., 2021; Fedele et al., 2014), photochemical oxidant formation (Zingale et al., 2022; Fedele et al., 2014), terrestrial acidification (Pelletier et al., 2008; Rebolledo-Levia et al., 2022; Gonzales-Garcia et al., 2021; Williams et al., 2010; Zingale et al., 2022; Fedele et al., 2014), freshwater and marine eutrophication (Rebolledo-Levia et al., 2022; Gonzales-Garcia et al., 2021; Williams et al., 2010; Zingale et al., 2022; Fedele et al., 2014), land occupation (Kamali et al., 2017; Fedele et al., 2014) and fossil fuel depletion (Rebolledo-Levia et al., 2022; Gonzales-Garcia et al., 2021; Pelletier et al., 2008; Fedele et al., 2014). Nevertheless, the context-dependent nature of agricultural LCAs, specifically with respect to agroclimatic factors, means that more data are needed that reflect conditions on specific farms. This is particularly true for organic systems, which are often managed under heterogeneous conditions that include diverse fertilization inputs, field operations, and land management.

3.2.1.2 Findings from Organic LCA Studies

Table 3-1 to Table 3-4 presents the GWPs expressed as kg CO_2eq t^{-1} of crop output of organic field crops from cradle-to-farmgate from a sample of LCA studies undertaken around the world. In addition, when available, data related to the contributions from nutrient application, field operations, and seed provision were also included. It is important to note that production-related emissions for field crops vary across regions due to differences in plant species, agro-climatic conditions, soil type, and management practices (Moudry et al., 2013).

A considerable number of studies assessed the environmental impacts of organic wheat, with results ranging from -99 to 980 kg CO_2eq t^{-1} (average 502 kg CO_2eq t^{-1}) (Table 3-1). Results from Moudry et al. (2013), Chiriaco et al. (2017), and Moudry et al. (2018) demonstrate that a significant proportion of contributions to GWP are due to nutrient application and field operations. Chiriaco et al. attributed the fuel used for agricultural equipment during cultivation, and soil emissions, including direct and indirect N_2O, as major contributions to the GWP (2017). In addition, they note that the lower yield per unit area also caused relatively high GHG emissions (Chiriaco et al., 2017). Similarly, Pelletier et al. (2008) and Rebolledo-Levia (2022) both identified field level emissions and fertilization as ‘hotspots’ in their analyses. While patterns among studies have been consistent and point to the dominance of field level N emissions and field operations in organic wheat production, it is crucial to consider the heterogeneity of organic production systems, such as management practices, location, and crop yield that can influence the total GWP.

Knudsen et al. (2014) presented four results for the GWP of organic wheat (Table 3-1), which originate from four different management scenarios (different N supplies for four-year rotations with three cash crops: potatoes, winter wheat, and spring barley, and then fava bean or grass-clover as a green manure) averaged across three different locations in Denmark (Table 3-1). The management scenarios included a ‘mulching’ rotation (fava bean replaced by grass-clover and incorporated for soil fertility), a ‘biogas’ rotation (green manure is not incorporated but harvested and used for biogas production, biogas residues are returned to the field), a ‘slurry’ rotation (livestock manure is imported and applied), and a ‘no-input’ scenario (all four crops sold as cash crops, catch crops grown, but no organic fertilizer). GWP results for organic wheat from the ‘mulching’ rotation, ‘biogas’ rotation, ‘slurry’ rotation, and ‘no input’ rotation totaled 912, -99, 527, and 809 kg CO2 eq t^{-1} DM ha^{-1}, respectively. Results were variable due to vast differences in management practices (e.g. environmental burdens inherited from green manures and catch crops and varying levels of fertilization), soil carbon changes, and yield (one location had unfavourable conditions that resulted in lower yields) (Knudsen et al. 2014). Importantly, Knudsen et al. (2014) included soil carbon changes in their analysis using an approach by Petersen et al. (2013), which estimates that 10% of added carbon to the soil will be sequestered in a 100-year perspective. While Knudsen et al. (2014) didn’t provide specific soil carbon changes of organic wheat production, they illustrated in a figure that the ‘mulching’ rotation (described above) had the highest soil carbon accumulation, followed by ‘biogas’ and ‘slurry’ rotations (described above), while the ‘no input’ rotation experienced a decrease in carbon due to lower yields and thus fewer crop residues and the resulting lower carbon input. Similar to prior studies, the dominant contributions to GWP were field level N emissions and field operations, but also soil carbon changes and site-specific management conditions (i.e. yield, rotation, and location) that can vastly influence total impacts.

Similarly, Chiriaco et al. (2017) and Zingale et al. (2022) both conducted an LCA of organic wheat in Italy and found the total GWP to be 980 and 202 kg CO2 t^{-1}, respectively (Table 3-1). While yield was not disclosed in Zingale et al. (2010), yields were very low in Chiriaco et al. (2017), which is one reason for the discrepancy in total GWP. In addition, among production yields, the comparison between these studies is affected by the fact that soil organic carbon was considered in the study by Zingale et al. (2022), while Chiriaco et al. (2017) did not. Therefore, another limitation to the robustness of organic LCA results and accurate comparisons is the inconsistent application of SOC quantification to account for site-specific differences that can influence final GWP results.

Table 3-1 Total Global Warming Potential (GWP) results including contributions from nutrient application, field operations, and seed (if available) from cradle-to-farmgate organic wheat LCAs

Crop	Yield (t/ha)	Total GWP (kg CO_2 eq/ t)	Nutrient Application (kg CO_2 eq/ t)	Field Operations (kg CO_2 eq/ t)	Seed (kg CO_2 eq/ t)	Geographic Area	Reference
Wheat	2.4	382	-	-	-	Canada	Pelletier et al., 2008
	4.5	492*	-	-	-	Spain	Rebolledo-Levia et al., 2022
	5.4	578*	-	-	-		
	5.0	153*	-	-	-		
	-	462	289	75		Czech Republic	Moudry et al., 2013
	3.5	423	187	132	35	Czech Republic and Central Europe	Moudry et al., 2018
	4.1	786	-	-	-	England & Wales	Williams et al., 2010
	3.7	527*	-	-	-	Denmark	Knudsen et al., 2014
	1.7	809*	-	-	-		
	4.0	-99*	-	-	-		
	2.3	912*	-	-	-		
	1.5	980	420	460	100	Italy	Chiriaco et al., 2017

-	202*	-	-	-	Italy	Zingale et al., 2022

*hyphen in a cell represents data that was not provided
*asterisk refers to total GWP including soil carbon change

Pelletier et al. (2008) and Rovelledo-Levia et al. (2022) provided results for organic corn from cradle-to-farmgate (Table 3-2). They reported emissions of 256 and 455 kg CO_2eq t^{-1}, respectively. Again, Pelletier et al. attributed results to fertilization and field emissions (2008). Rebolledo-Levia et al. note that corn represented 64% of the impacts in a rotation of Galician wheat-oilseed rape, corn, and lupine (2022). Similarly, GWP impacts were the result of field emissions by fertilization, which caused high N_2O emissions (Rebolledo-Levia et al. 2022).

Table 3-2 Total Global Warming Potential (GWP) results from cradle-to-farmgate organic corn LCAs

Crop	Yield (t/ha)	Total GWP (kg CO_2 eq/ t)	Geographic Area	Reference
Corn	6.8	256	Canada	Pelletier et al., 2008
	-	455	Spain	Rebolledo-Levia et al., 2022

*hyphen in a cell represents data that was not provided

GWP results from three soybean LCA studies where organic management was applied were compiled and compared in Table 3-3. Results are fairly comparable across the literature. Guareschi et al. evaluated nineteen organic soybean operations in Brazil (2019). When averaged, their result was attributed to five main sources of GHG emissions: fuel (31.6%), 2) seeds (27.9%), 3) organic fertilizer (18.4%), 4) liming (10.2%), and 5) tractors and agricultural machinery (7.4%). Results from Kamali et al. (2017) differ from Pelletier et al. (2008) due to differences in assumptions concerning fertilization. While Pelletier et al. (2008) assumed only phosphate rock for P fertilization, Kamali et al. (2017) assumed half manure and half phosphate rock for organic P fertilizer, in which manure application was a contribution to a higher GWP.

Table 3-3 Total Global Warming Potential (GWP) results including contributions from nutrient application, field operations, and seed (if available) from cradle-to-farmgate organic soybean LCAs

Crop	Yield (t/ha)	Total GWP (kg CO_2 eq/ t)	Nutrient Application (kg CO_2 eq/ t)	Field Operations (kg CO_2 eq/ t)	Seed (kg CO_2 eq/ t)	Geographic Area	Reference
Soy	2.4	190	-	-	-	Canada	Pelletier et al., 2008
	2.5	190	59	72	51	Brazil	Guareschi et al., 2019
	2.7	270	-	-	-	Brazil	Kamali et al., 2017

*hyphen in a cell represents data that was not provided

GWP results from two organic oat studies and one organic rye study are included in Table 3-4. Similar to the results of wheat, corn, and soy from the studies discussed thus far, contributions from nutrient application and field operations constitute the greatest proportion of impacts (Moudry et al., 2018). Viana et al. identified the use of organic fertilizers and manure transport as hotspots in their organic oat production analysis (2022). Both Viana et al. (2022) and Moudry et al. (2018) mention the relationship between yield and environmental performance; a disadvantage discussed in both studies was the lower production per area unit, which increased emissions per tonne output.

Table 3-4 Total Global Warming Potential (GWP) results including contributions from nutrient application, field operations, and seed (if available) from cradle-to-farmgate organic oat and rye LCAs

Crop	Yield (t/ha)	Total GWP (kg CO_2 eq/ t)	Nutrient Application (kg CO_2 eq/ t)	Field Operations (kg CO_2 eq/ t)	Seed (kg CO_2 eq/ t)	Geographic Area	Reference
Oat	3.0	436	-	-	-	Canada, Quebec	Viana et al., 2022
	2.6	303	123	116	27	Czech Republic and Central Europe	Moudry et al., 2018
Rye	2.9	298	116	113	26	Czech Republic and Central Europe	Moudry et al., 2018

*hyphen in a cell represents data that was not provided

*asterisk refers to total GWP including soil carbon change

Results for LCA studies of organic field crop production that reported impact categories other than GWP are presented in Table 3-5. Results are fairly comparable among similar crop types with some exceptions, which may be the result of differences in geographic and management conditions. Impacts related to ozone depletion are often most influenced by nitrous oxide, carbon monoxide, and methane (Rebolledo-Leiva et al., 2022). For categories such as acidification potential, the most relevant contribution is NH_3 (ammonia) emissions from the field related to nitrogen fertilizer application (Rebolledo-Leiva et al., 2022; Pelletier et al., 2008). For freshwater eutrophication, the critical hotspot is phosphate emissions into water (Rebolledo-Leiva et al., 2022 & Gonzáles-García et al., 2021). The major hotspots regarding toxicity-related categories are copper and zinc due to machine use for tillage, sowing, and fertilizer application (Rebolledo-Leiva et al., 2022). Field operations such as tillage, sowing, and harvesting activities are main drivers of fossil resource scarcity due to crude oil consumption (Rebolledo-Leiva et al., 2022). As discussed previously, lower yields in organic production systems result in high land occupation required to produce outputs similar to conventional systems (Kamali et al., 2017). Last, while energy use in organic systems are less than that of conventional systems (Pelletier et al., 2008; Kamali et al., 2017), primary drivers include fuel fuel use (Pelletier et al., 2008; Kamali et al., 2017) and mineral-based fertilizer production (Pelletier et al., 2017).

Table 3-5 Cradle-to-farmgate impact results for organic field crops from nine additional impact categories

Crop	**Impact Category and Value**	**Study Location**	**Reference**
	Ozone Depletion (kg CFC-11 eq / t)		
Wheat	8.00E-07	Canada	Pelletier et al., 2008
Corn	6.60E-06	Canada	Pelletier et al., 2008
Soybean	5.00E-06	Canada	Pelletier et al., 2008
Soybean	1.57E-06	Italy	Fedele et al., 2014
	Freshwater Ecotoxicity (kg 1.4-DB eq/ t)		
Soybean	5.1	Italy	Fedele et al., 2014
Oat	2.6	Canada, Quebec	Viana et al., 2022
	Terrestrial Ecotoxicity (kg 1.4-DB eq/ t)		
Soybean	1.75E-01	Italy	Fedele et al., 2014
Oat	983.9	Canada, Quebec	Viana et al., 2022
	Photochemical Oxidant Formation (kg NMVOC eq/t)		
Soybean	2.2	Italy	Fedele et al., 2014
Wheat	1.5	Italy	Zingale et al., 2022
	Acidification Potential (kg SO_2 eq/ t)		
Wheat	9.7	Canada	Pelletier et al., 2008
Wheat	1.2	Italy	Zingale et al., 2022

Crop	Impact Category and Value	Study Location	Reference
Wheat	3.1	Italy	Verdi et al., 2022
Wheat	3.3	England & Wales	Williams et al., 2010
Soybean	2.2	Italy	Fedele et al., 2014
Soybean	5.7	Canada	Pelletier et al., 2008
Corn	5.4	Canada	Pelletier et al., 2008
Oat	13.1	Canada, Quebec	Viana et al., 2022
	Freshwater Eutrophication (kg PO_4-^{3} eq/t)		
Wheat	3.4	Italy	Zingale et al., 2022
Wheat	1.6	Italy	Verdi et al., 2022
Wheat	9.3	England & Wales	Williams et al., 2010
Soybean	0.3	Italy	Fedele et al., 2014
	Land Occupation (m^2 eq/ t)		
Wheat	4100	England & Wales	Williams et al., 2010
Soybean	2627	Italy	Fedele et al., 2014
Soybean	2377	Brazil	Kamali et al., 2017
Oat	1740	Canada, Quebec	Viana et al., 2022
	Fossil Depletion (kg oil eq/ t)		
Soybean	28.2	Italy	Fedele et al., 2014
Oat	54.2	Canada, Quebec	Viana et al., 2022

Crop	Impact Category and Value	Study Location	Reference
	Energy Demand (MJ/t)		
Wheat	800	Canada	Pelletier et al., 2008
Wheat	5340	Italy	Verdi et al., 2022
Soybean	1500	Canada	Pelletier et al., 2008
Soybean	2149	Brazil	Kamali et al., 2017
Corn	1300	Canada	Pelletier et al., 2008

3.2.1.3 Soil Organic Carbon changes in Organic LCA Studies

Importantly, a significant limitation to LCA results reported to date is the inconsistent inclusion of soil organic carbon (SOC) dynamics (i.e. gains and losses of carbon in the soil). Indeed, many organic LCA studies do not include SOC (e.g. Almeida-Garcia et al., 2022; Pelletier et al., 2008; Hoffman et al., 2018; Chiriaco et al., 2017; Moudry et al., 2013). Peterson et al. (2013) notes that a majority of LCA studies of agricultural production systems do not include soil carbon changes due to methodological limitations and limited consensus on standard procedures. Such uncertainties include the optimal estimated depth of the soil profile (spatial system boundary), an optimal time horizon (e.g. 20, 30, 100, or 200 years), as well as soils approaching a new ‘steady state’ or equilibrium and soil C saturation.

For those studies that have recently started to include SOC changes, there are mixed results. Liang et al. (2017) conducted a partial LCA to assess the effects of potential feeding strategies, along with their associated crop production, on GHG emissions of Wisconsin certified organic dairy farms. Without accounting for changes in SOC, GHG emissions from crop production were 1, 297 kg CO_2 eq t^{-1} of ECM (energy corrected milk), and with SOC, GHG emissions totaled 1, 457 kg CO_2 eq t^{-1} of ECM (energy corrected milk) (Liang et al., 2017). While this study did not demonstrate carbon sequestration, but soil carbon loss in all production strategies, it is apparent that SOC affected overall GHG emission estimations. Rebolledo-Leiva et al. (2022) and Gonzáles-García et al. (2021) assessed soil carbon in their studies and found reductions in total GHG emissions from production due to carbon storage. Straw returns and additions of residue biomass to their cropping system increased the soil carbon content, which contributed to reduced GHG emissions from each cropping system (Rebolledo-Leiva et al., 2022).

Crop residues are carbon-rich sources for soil microbial activity that ultimately support increases in SOC concentrations (Zhu et al., 2014). Rebolledo-Leiva et al. (2022) found that the carbon stored in the soil as a result of straw decomposition ranged between -1880 and -629 kg CO_2 eq t^{-1} for the three organic rotations assessed in their analysis. The larger end of the range (-1880 kg CO_2 eq t^{-1}) was associated with large amounts of rapeseed straw alongside straw of wheat and lupine returned to the field, while the lower of the end of the range (-629 kg CO_2 eq t^{-1}) refers to only straw of wheat and lupine returned (Rebolledo-Leiva et al., 2022). Similarly, Gonzáles-García et al. (2021) found that retuning biomass to the field resulted in GHG emission reductions in all of the systems they assessed with carbon storage values ranging from – 15 to – 1071 kg CO_2 eq t^{-1}. Kimming et al. (2011) conducted an LCA of two systems for total energy self-sufficiency on an organic arable farm, and quantified the energy efficiency, resource use, and impact on GHG emissions. Using the Introductory Carbon Balance Model (ICBM), Kimming et al. (2011), modelled the carbon balance of cropping systems, and found through sensitivity analysis that the initial soil carbon concentration is an important parameter for the carbon balance of the system. Notably, the initial soil carbon content is one of the most crucial factors for determining the rate of carbon mineralization (Kimming et al., 2011) and should be accounted for when assessing the environmental performance of an agricultural production system. Therefore, despite its importance, assessing changes in soil carbon is also limited by robust data regarding site-specific conditions (Kimming et al., 2011).

With the exception of Kimming et al. (2011), who described their use of the ICBM model to simulate the carbon balance of their cultivation systems, the other studies that included SOC did not describe how they determined this parameter.

3.2.1.4 Practices for Reducing Impacts from LCA of Organic Production

The environmental performance of organic production systems is dependent on factors such as location and production practices, indicating the potential for improved production efficiency and sustainability (Knudsen et al., 2014; Pelletier et al., 2008). Recommendations and best practices to reduce on-farm energy use and GHG emissions include using low-impact nutrient sources and fertilizers, improved yields through appropriate nutrient management, and increased crop rotation length and complexity to improve soil and ecosystem health (Hoffman et al., 2018; Knudsen et al., 2014; Meisterling et al., 2009; Pelletier et al., 2008). For instance, inclusion of a leguminous crop in rotation can reduce or eliminate the need for external fertilizer inputs because legumes, grown at sufficient densities, are capable of meeting the N requirements of the subsequent crop in rotation, thus reducing further environmental burdens (Almeida-Garcia et al, 2022 & Gonzáles-García et al., 2021).

LCAs of organic crop production systems are currently constrained by the lack of high-quality data, misrepresentations of the heterogeneity of organic production systems, inconsistent methodological decisions, and inconsistent soil organic carbon reporting (Kamali et al., 2017; Peterson et al., 2013; Hu et al., 2018). The identification and application of best practices to improve environmental performance of organic agriculture can also be integrated into conventional production systems to reduce environmental impacts while maintaining high yields. A well-documented challenge concerning agricultural optimization concerns strategies to improve yields and the efficiency of inputs without compromising environmental impacts. Robust agricultural LCAs with transparent methodology, reporting, and high-quality primary data are required to advance LCA methodology, support agricultural producers, and suggest best management practices in the face of drastic environmental changes.

3.2.2 Research Question and Objectives

The research question guiding this analysis is as follows: What are the environmental impacts of organic field crop production in Eastern Canada? Given this question, the overall objective is to characterize the environmental profile of organic field crops in Ontario and Quebec and understand the underlying drivers of the impacts. This analysis will address the following sub-objectives:

1) Quantify the environmental impacts of organic field crop production based on the influence of agro-climatic differences;
2) Understand the influence of yield on overall impacts;
3) Identify areas of improvement based on underlying drivers of impacts;

3.3 Methodology

Life cycle assessment, coupled with modelling changes in soil organic carbon, was used to evaluate contributions to the life cycle GHG emissions and other impact categories selected that arise from the production of wheat, corn, and soybeans under organic management in Ontario and Quebec. LCA studies consist of four steps: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA), and (4) life cycle interpretation. The following methods section will follow this LCA standard format.

3.3.1 Goal and Scope Definition

The goal of this is to quantify and compare the cradle-to-harvest gate net contributions to impact categories that result from organic wheat, corn, and soybean production in the Eastern Canadian provinces of Ontario and Quebec.

The scope of the study describes the study design parameters, meaning the methodological decisions made for the modeling of the product systems, and any general assumptions made about the system, which are described in the following sections.

3.3.1.1 Product System Description

The crops studied were soybean, corn, and wheat production in the Eastern Canadian provinces of Quebec and Ontario. While varieties of field crops are grown in each region (i.e., hard red winter wheat, soft red winter wheat, autumn wheat, and spring wheat) and planting times differ, this study treated each field crop as single crop types (i.e., wheat, corn, and soybeans). This study does not represent each variety or class of wheat, corn or soybean. Furthermore, the LCI data gathered through survey participation made it possible to portray a subset of farms and production practices in this analysis. Accordingly, the data is aggregated by crop-province combinations to analyze production-related resource use and emissions and maintain survey respondents’ anonymity. Therefore, this study does not represent the total organic production of wheat, corn, and soybeans in Eastern Canada. Instead, this study represents a smaller sample of potential average Eastern Canadian wheat, corn, and soybean crop production systems.

3.3.1.2 Functional Unit

The functional unit (FU) “is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related” (ISO, 2016a; ISO, 2016b). The function of the organic system is to produce a crop; therefore, the functional unit is one metric tonne of fresh harvested crop, referred to as “1 t”, or “1 t Canadian organic field crop harvested”. In this analysis, it is assumed that at harvest, moisture content for all wheat, corn, and soybeans are 14.6%, 15.6%, and 14.1%, respectively (Canadian Grain Commission, 2019).

3.3.1.3 System Boundaries

The boundaries of the Canadian organic field crop system analysis are the “cradle-to-harvest gate” production of crops grown between 2016 and 2021. Field crop production is the foreground of this system, which includes (where applicable), seed inputs, nutrient inputs and applications, field operations, land use, and their associated field-level emissions and soil organic carbon change. In addition, as Eastern Canadian wheat, corn, and soybeans are often grown in rotation with cover crops and green manures grown in advance of, or alongside, the field crops, these inputs are included in the boundary of the respective field crop. Specific field operation-related activities included in the analyses, when they were used include: application of plant protection and fertilizer products, combine harvesting, cultivating, harrowing, hoeing, land rolling, ploughing, sowing, and weeding. The analysis ends at the harvest gate and, therefore, does not include post-harvest operations such as storage, drying, and cooling as there was insufficient data given on these post-harvest operations to quantify these impacts. The temporal boundary is 2016 to 2022, which reflects the period in which LCI data were provided by farmers through survey participation. In most cases, participants provided their most recent crop inventory data (2018-2022), while some provided crop rotation data from prior years.

3.3.1.4 Co-product Modelling

In LCA, when a product system has two products (primary and a co-product), there needs to be an approach to assigning or ‘allocating’ impacts of production to each product. The ISO standard prioritizes avoiding allocation by dividing the unit process in question into sub-processes and collecting related input and output data for these sub-processes or by system expansion, but these methods require a significant amount of data to accomplish (ISO, 2016b). When allocation is unavoidable, often methods such as a physical relationship, including mass or energy, are used as a basis for the allocating process (Curran, 2015; ISO, 2016b). The co-products in the system were nitrogen from both soy production and green manures supplied to subsequent crops in a rotation. Such crops can be considered valuable products because they supply nutrients, particularly nitrogen, that support crop productivity and soil health (Leip et al., 2019). The environmental impacts were assigned to the soy and nitrogen based on physical allocation.

Manure was assumed to be a co-product of conventional livestock production, and was treated as a recycled product. This means that the environmental loads of the recycling of material from one production system to another are shared equally between two adjacent product systems (Lee & Inaba, 2004). Further details are provided in the LCI section 3.3.2.4.1.1.

3.3.1.5 Data Quality Requirements

To meet the goals of the study, the following data characteristics are required:

1) **Spatial:** This study provides a snapshot of cradle-to-harvest gate field crop production emissions across Eastern Canada, therefore to meet the goal of the study, data on production, energy use, and agricultural inputs should be from this region.
2) **Temporal:** Data should be within 10 years of the study to allow for averaging climate conditions that affect crop production, and to reflect the most current practices.
3) **Technological:** Data should be based on current management practices in organic farming.

3.3.1.6 Impact Assessment Method and Categories

The life cycle impact assessment is the third phase of the life cycle assessment methodology where life cycle inventory data is converted “into a set of potential impacts” (Laurin and Dhaliwal, 2017, p. 225). The use of distinguished impacts (i.e., impact categories for LCA) allows for the environmental impacts of systems or products to be easily comparable between one another; making impacts easier to understand for both LCA practitioners and decision makers alike (Laurin and Dhaliwal, 2017).

The impact assessment method IMPACTWorld+ was chosen to model impacts in openLCA. This LCIA method was chosen due the incorporation of the Canadian-specific modelling resolution from LUCAS (Bulle et al., 2007; Bulle et al., 2019). Furthermore, IMPACTWorld+ was one of the few LCIA methods that modelled all chosen elementary flows, including the land occupation flow "occupation, annual crop, organic" which was included amongst the impact categories deemed important to consider in this assessment. IMPACTWorld+ was used as a midpoint assessment method, meaning the "indicators are defined somewhere between the emission and the endpoint" (De Schryver et al., 2010, p. 177). Moreover, midpoint indicators are "considered to be links in the cause-effect chain (environmental mechanism) of an impact category, prior to endpoints, at which characterization factors or indicators can be derived to reflect the relative importance of emissions or extractions" (Bare et al., 2000, p. 1). This differs from endpoint indicators in that the endpoint method considers the end of the cause-effect chain and frequently shows results as they relate to human or environmental health (Meijer, 2021).

Furthermore, in life cycle impact assessments, environmental flows are classified based on the resource depletion or environmental impacts they contribute to, and multiplied by a characterization factors (CF) that are used to compute the contribution to an indicator in a single consistent reference species, like CO_2 for all GHG emissions (Levasseur et al., 2016). CFs are used to estimate the relative or absolute effect of each flow on an indicator and expresses a quantified representation of an impact category (Levasseur et al., 2016). Specific LCIA methods, such as IMPACTWorld+, identify CFs for different environmental impacts (ISO 14044, 2016). IMPACTWorld+ can account for environmental impacts at different levels of spatial resolution (e.g. global, national, and regional) (Bulle et al., 2019). For midpoint level impact categories assessed in this study, which includes climate change (long term), fossil and nuclear energy use, freshwater acidification, freshwater eutrophication, land occupation and biodiversity, and water scarcity the corresponding midpoint level characterization factors units are $\text{kg CO}_{2\text{ eq(long)}}/\text{kg}_{\text{emitted}}$, $\text{MJ}_{\text{deprived}}/\text{kg}_{\text{dissipated}}$, $\text{kg SO}_{2\text{ eq}}/\ \text{kg}_{\text{emitted}}$, kg PO_4 P-lim eq/ $\text{kg}_{\text{emitted}}$, $\text{m}^2_{\text{arable land eq}} \cdot \text{yr}/\ (\text{m}^2_{\text{occupied}} \cdot \text{yr})$, $\text{m}^3_{\text{world-eq}}/\text{m}^3_{\text{consumed}}$, respectively (Bulle et al., 2019).

The impact assessment categories applied in this analysis are climate change (long term) (CCLT), fossil and nuclear energy use (EU), freshwater acidification (FA), freshwater eutrophication (FE), land occupation (LO), and water scarcity (WS).

In IMPACTWorld+, the climate change characterization factor refers to the radiative forcing of a GHG relative to the radiative forcing of carbon dioxide (Bamber et al., 2021; Dodd et al., 2020). The IPCC Global Temperature Potentials for a 100-year time horizon (GTP100), is the midpoint indicator for climate change (long term), which represents "a change in global mean surface temperature at a chosen point in time" (Bulle et al., 2019, ESM p. 9). While it is not a cumulative indicator, it is considered an appropriate proxy for representing climate change long-term impacts (Bulle et al., 2019; Levasseur et al., 2016). Thus, using GTP100 as the indicator for climate change (long term) expresses the contributions of GHG emissions to long-term temperature increases and cumulative warming (Bulle et al., 2019). This impact category differs from shorter-term climate change, which adopts GWP100 as the midpoint indicator (Bulle et al., 2019). Climate change (long term) impact results are expressed as kg CO_2 (long) (Bulle et al., 2019).

Expressed as MJ deprived, the fossil and nuclear energy use impact category represents the depletion of non-renewable, abiotic resources (Bamber et al., 2021), much like the Abiotic Resource Depletion Potential category commonly found in older LCAs. In IMPACTWorld+, "the material competition scarcity index is applied as a midpoint indicator" for the mineral resources' depletion impact (Bulle et al., 2019, p. 1).

Freshwater acidification, sometimes referred to as acidification potential, is the second most investigated impact category in the literature (Dincer and Bicer, 2018). This impact category refers to the acidifying of water and soil by contaminating substances (Dincer and Bicer, 2018). The IMPACTWorld+ methodology combines soil and water ecosystem sensitivity with global atmospheric source-deposition relationships. Freshwater acidification is expressed as kg SO_2 eq.

The freshwater eutrophication category measures the discharge of nutrients, mostly nitrogen and phosphorous, into freshwater bodies or soil (Azevedo et al., 2014). According to Bulle et al. (2019), using the IMPACTWorld+ methodology, freshwater eutrophication is based on a global hydrological dataset and assessed at a resolution grid of 0.5 degrees x 0.5 degrees. This impact category is expressed in units of kg PO_4 eq.

The land occupation category measures the effect of land occupation on biodiversity loss over a given period of time (Bamber et al., 2021). In addition, according to Bulle et al. (2019), land occupation (and land transformation) is considered an acceptable proxy for the impacts of land use on ecosystem services. This category is expressed as m^2 arable land eq-yr. Impacts are characterized at the biome level, according to the IMPACTWorld+ methodology (Bulle et al., 2019).

Water scarcity refers to the impacts from water consumption (Bulle et al., 2019). IMPACTWorld+ adopts the water scarcity AWARE model (Boulay et al., 2016) at the midpoint level as a proxy for all water scarcity impacts. This impact category considers the water available per area after human and aquatic ecosystem demands are met, relative to the world average (Bulle et al., 2019). The AWARE model is recommended by the UNEP/SETAC Life Cycle Initiative, and the European Commission (Bulle et al., 2019). This impact category is expressed in units of m^3 world-eq.

3.3.1.7 Cut-off Criteria

Post-farmgate operations were not considered in this analysis. Furthermore, this analysis does not include nutrient inputs to production applied at less than 0.9 kg ha^{-1}. Mineral or other amendments that were not included were sugar, molasses, microbial tea, and humic acid; each were applied at rates below the 0.9 kg ha^{-1} cut-off. The next lowest application rate is approximately 4.5 kg ha^{-1}. Thus, there is an approximately 400% difference between the application rate of inputs included and the lower input cut-off applied. Importantly, the excluded mineral amendments only occur on one farm. Therefore, at application rates of less than 0.9 kg ha^{-1}, these inputs environmental impacts were deemed inconsequential compared to the numerous other mineral and non-mineral amendments included in the analyses.

3.3.2 Life Cycle Inventory

The life cycle inventory (LCI) step involves building an inventory of all input and output flows for the product system, including raw materials, energy, emissions, waste, etc. (ISO, 2016a; ISO, 2016b). The first step is to draw a flow diagram that captures all the relevant activities and processes associated with the product system. The foreground system consisted of all on-farm activities as shown in Figure 3-1.

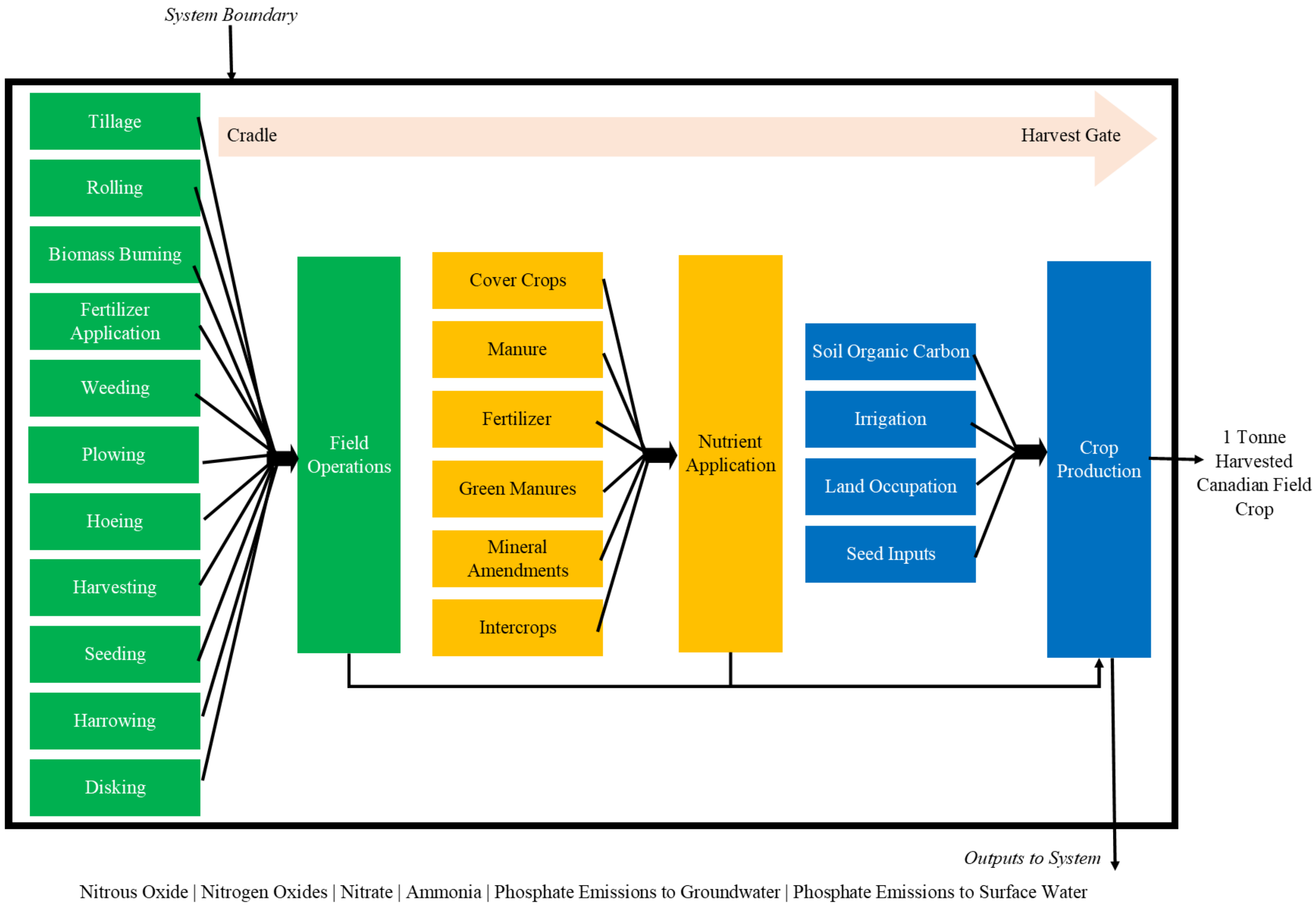


Figure 3-1 System boundaries for modeling central Canadian organic wheat, corn, and soybean production

3.3.2.1 Organic Farm Foreground Data Collection

Based on a literature review of LCAs of organic field crop production (Bamber et al. 2022), a survey was developed to elicit details of organic field crop production practices known to make potentially important contributions to life cycle impact assessment results. The resulting survey included questions related to farm location, history of organic management, details regarding current rotation practice, and for at least one or more crops grown in that rotation, details related to seeded area, yield, and seeding rate (the full survey appears in Appendix A). The producers who were surveyed met the following criteria:

- 18 years of age or older, and
- Have inventory data for a Canadian field crop farm operating under organic standards (i.e. organic certification or organic management practices).

Since a formal list of organic Canadian field crop producers was not available, Google searches of Canadian organic field crop farms were performed to compile a list of potential participants. Search terms included the following:

- Canadian organic farm; Canadian organic field crop farm; Canadian organic producer; [Province] organic [field crop] farm; [Province] organic [field crop] producer

From this list of potential participants, each was contacted by phone or email (based on publicly available contact information found via Google searches) to request their participation in the study's survey. For those producers who agreed to participate, a detailed survey was sent to them by email, mail, an online link, or they were given the option to complete the survey during a walkthrough with a researcher. The questions asked producers about their farm location, management practices (crops grown, nutrient applications, field operations, irrigation, pest control, and cover crop/green manure management), and an optional demographic questionnaire. Participants were contacted a maximum of three times either by phone or email. A total of 50 surveys were completed which gave 144 farm-crop combinations to model for life cycle GHG emissions and other associated life cycle environmental impacts. A farm-crop combination is one crop grown in one year on one farm (e.g., a farm with a single field two-year soy-corn rotation that provided data for both their soy and their corn production has two farm-crop combinations).

For many inputs described by farmers, further details regarding their composition and origins were needed (e.g. types of manure, their moisture, N, P, K and C contents, etc). Details regarding these attributes were first sought from farmers who applied them. Where additional characteristics were required, these were sought from reputable sources (e.g. various nutrient manufacturer’s websites for NPK). Furthermore, land management history (i.e. the number of years a farm has been under its current organic management practice and land management history prior to current practices) was collected from producers to calculate field-level emissions, such as soil carbon changes.

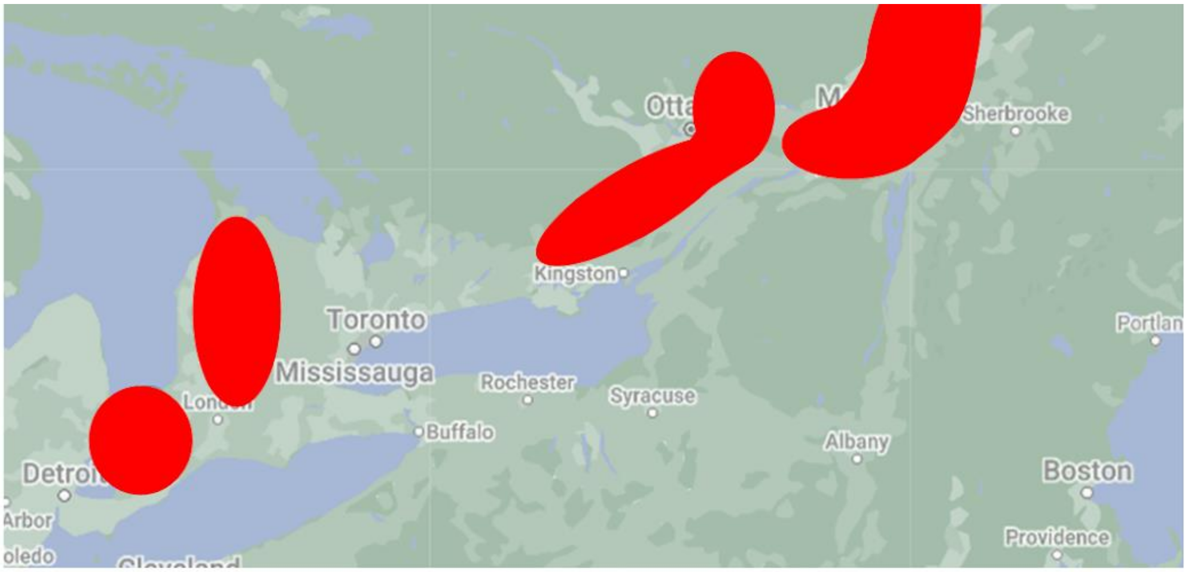
Results of the inventory data collection effort analyzed here report results for organic wheat, corn, and soybean production data from 18 farms across Ontario and Quebec totaling 33 farm-crop combinations (Table 3-6). The approximate geographic location of farms that provided data is shown in Figure 3-2. Due to the limited number of respondents, farms are clustered in groups with a minimum of three to maintain anonymity. The location of the farms in Figure 3-2 correlates with the production of wheat, corn, and soybean production in the major growing regions of Ontario and Quebec.

Table 3-6 Breakdown of total farm-crop combinations for wheat, corn, and soybeans by province (Ontario and Quebec).

Province	Crop(s)	Number of Farm-Crop Combinations
Ontario	Wheat	5
	Corn	6
	Soybean	9
Quebec	Wheat	4
	Corn	4
	Soybean	5

Prior to modeling, all data were reviewed for completeness and seeming outlier data. Where concerns were identified, farmers were re-contacted for clarification. In addition, to ensure yields reported were reasonable they were compared against the 2021-2022 averages of wheat, corn, and soybean yields from eastern Canada from the Agriculture and Agri-Food Canada and Statistics Canada’s November Farm Survey results of crop production (Agriculture and Agri-food Canada, 2022a).

Figure 3-2 Approximate locations of Eastern Canadian farms that provided data for this analysis. Red clusters indicate a grouping of three or more farms to maintain producer anonymity.



3.3.2.2 Background Data

The life cycle database, ecoinvent version 3.8 (Moreno Ruiz et al., 2021) was used for background processes and inputs, such as fossil fuel, electricity, nutrients, etc. These existing processes were modified to best represent, where applicable, provincial-, Canadian-, or North American-specific inputs such as electricity, production practices, water, and other inputs. A full list of modified processes with their modifications is found in Appendix B. Importantly, where possible, preference was given to provincial-specific providers of an input to the model, followed by Canadian-specific providers, then to Rest-of-North American, and finally to U.S. or Rest-of-World if a provincial option was not available. There were no modifications made to field operation (i.e. tillage, harrowing, sowing, etc.) because all embedded processes were already representative of the specified geography. For manure inputs, or rather the industrialized fertilizer manufacturing processes representing manure, processes were modified to represent the geography where those industrial fertilizers are manufactured according to the Carbon Footprints for Canadian Crops: Canadian Fertilizer Production Data, Table 7 (Cheminfo Services Inc., 2016). Similarly, mineral amendment inputs were modified such that the embedded flows are representative of the location in which they are produced (See Appendix Q).

Life cycle inventories for upstream processes (production of seed inputs, field operations, mineral amendments, manure inputs, and crops) were sourced from the ecoinvent databases, which provided the most similar geographical, temporal, and technologically data to that of Eastern Canadian organic field crop production conditions. When possible, Canadian-specific inventories were chosen, and if they did not exist, inventories from the United States, Europe, or ‘Rest of World’ were selected and modified to represent Canadian conditions. Modifications to inventory data involved changing the location for providers of select flows in a process, such as province-specific electricity and heat providers (see Appendix B for all modifications of processes drawn from ecoinvent v 3.8).

3.3.2.3 Data Quality and Uncertainty

The LCI data used in this LCA study includes primary data provided by Canadian organic field crop farmers, published literature, government reports, and databases. In general, the primary data collected from Canadian farmers were representative of real organic field cropping production systems. However, in several instances, farmers were re-contacted to clarify units, the magnitude of values, missing data points, and any uncertainties in understanding how a farm was operating in space and time to ensure accuracy. Overall, a majority of farmers provided their most recent data up until 2021. However, a considerable area of uncertainty pertains to the limited number of datasets, which inhibits this study from drawing general conclusions regarding the environmental performance of organic field crop production for an entire province or region in Canada. There is always some uncertainty with the inputs to a farm-crop model and primary data may not always be available for all inputs. Uncertainty concerning missing primary data was addressed using proxy data, expert opinion, and triangulation with secondary data sources.

This study also references and sources data from secondary data sources, such as published literature, government reports, websites, and databases. When possible, secondary sources of data were temporally and geographically relevant, such as within the last five years, Canadian, or representative of Canadian production conditions, or were generally reflective of a crop or the composition of an input. These decisions and approximations are not ideal but ensure relevant LCI data are used whenever possible. Moreover, LCIs also reflected and incorporated the most representative technology mix present in Eastern Canadian organic field crop production systems in accordance with LCI data gathered from survey participants regarding their management practices.

3.3.2.4 LCA Model Structure

The life cycle assessment modeling software openLCA 1.11 (2021) from GreenDelta was used to model and quantify impacts of wheat, corn, and soybeans grown under organic management in Eastern Canada. The model structure was created within openLCA as a series of “nested processes” for each crop, which contained all the life cycle inventory data for that crop (Figure 3-3).

Just as Russian Nesting Dolls are stacked one inside the other, the nested processes spreadsheet is similar

Seed inputs, nutrient, application, field operations, and post-harvest are all processes nested within the production process.

Further imbedding reveals processes such as cover crops, manure inputs, green manures, and mineral amendments nested within nutrient application.

The nested processes branch out to include multiple layers of nesting, all modelled in OpenLCA

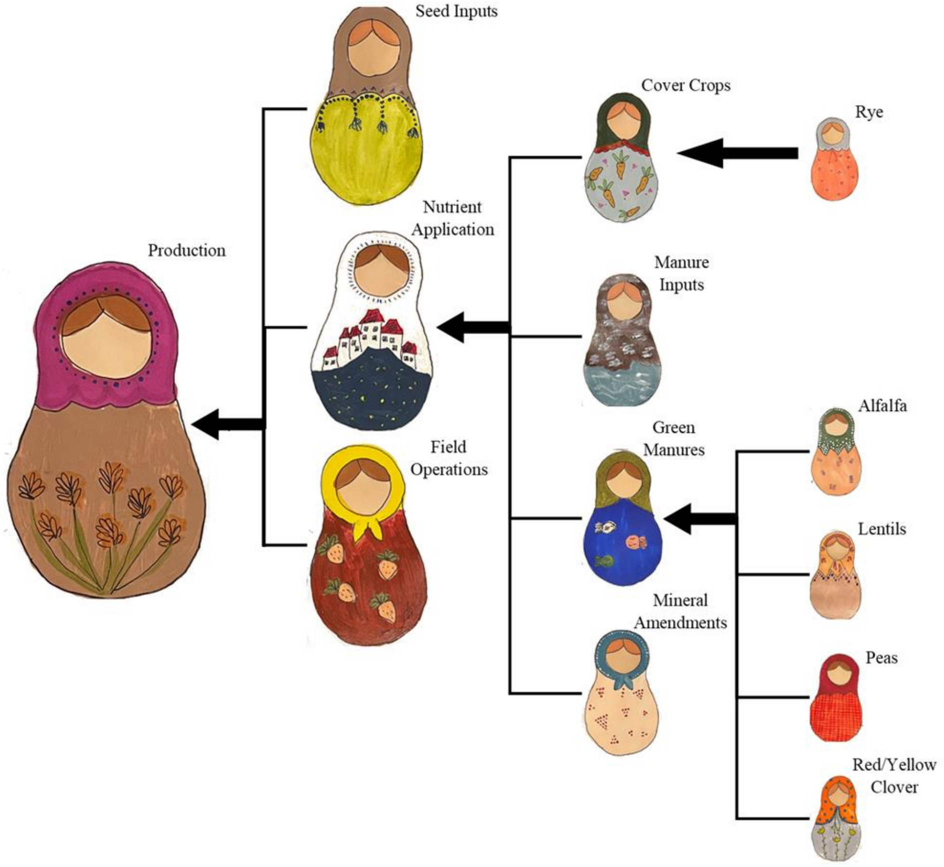


Figure 3-3 High-level overview and explanation of nested processes structure

The following sections provide more details of how each nested process was modeled:

Field Operations: The main field operations were: hoeing; sowing; swathing; tillage, cultivation, plowing, and rolling; harrowing, fertilizing; spraying of plant protection products; harvesting. Activity levels (i.e. the use of machinery) were calculated based on how many passes of each operation occurred (e.g. two passes of a cultivator) over the area required to produce 1 tonne of crop. Details of processes and providers used from ecoinvent are provided in Appendix E.

Seed Inputs: The life cycle inventory for seed production was obtained from ecoinvent. The seed inputs included: organic seeds for barley, fava bean, grass, corn, pea, potato, rape (canola), rye, soybean, and wheat (used for both wheat and buckwheat crops, since buckwheat did not exist in the ecoinvent database). The ecoinvent database also did not contain organic seed for lentil and oat, so generic lentil and oat processes were used. The providers for each of the seeds can be found in Appendix F.

Nutrient Application: Nutrient applications (see Appendix G) included manure (Appendix H), green manure (Appendix H), cover crops (Appendix J), and mineral amendments (Appendix K). Nutrient transportation was assumed to travel 8 km by freight transport (i.e. 7.5-16 metric tonne lorry, EURO6). Details of how these inputs were modeled are described below.

3.3.2.4.1 Modeling Nutrient Inputs

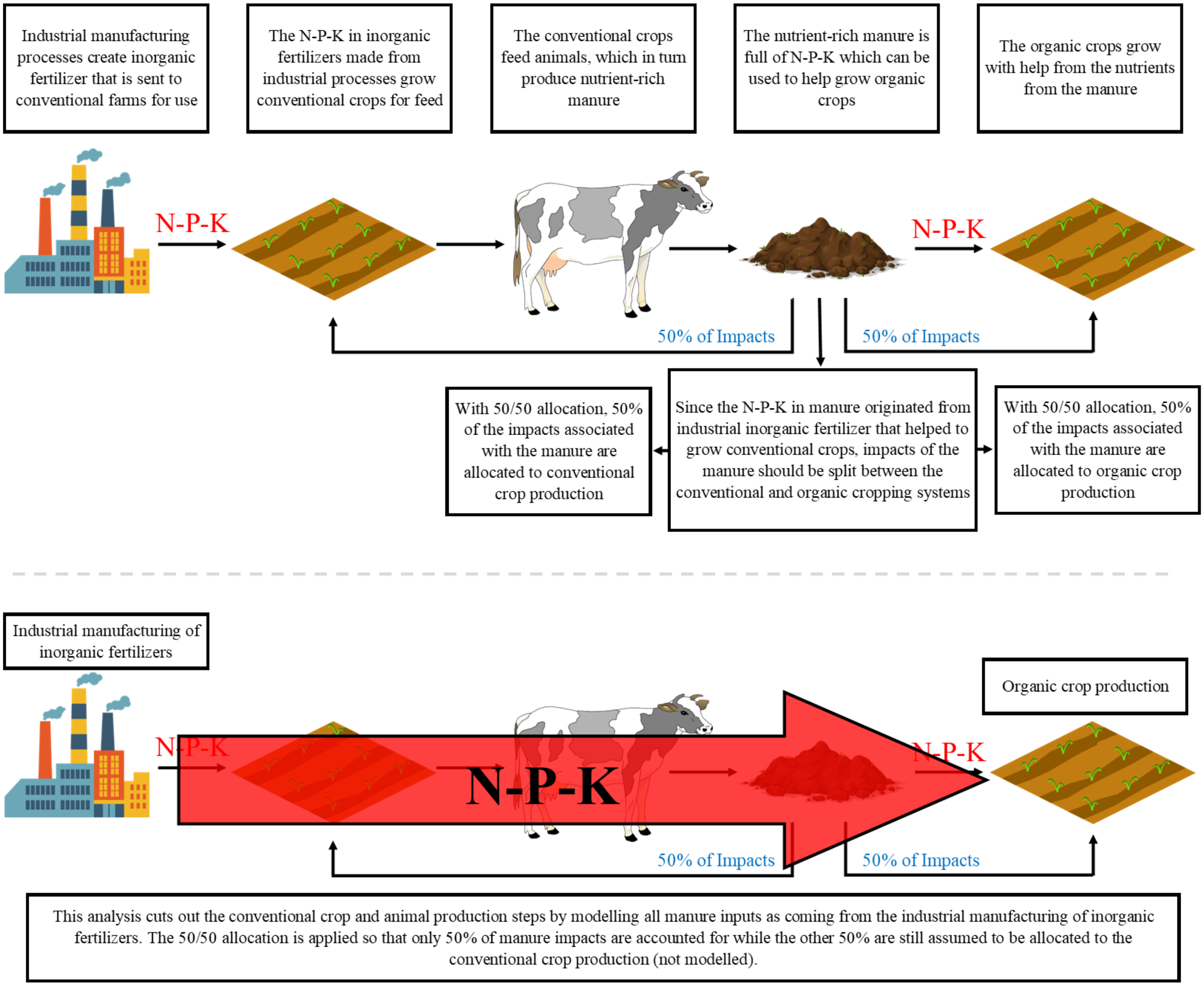
3.3.2.4.1.1 Manure

In the farm inventory data provided by farmers, many specified that nutrients were supplied through animal manure (e.g. from cattle, poultry, swine, or horse) in either liquid or solid forms, as well as their application rates. It was assumed that all manure was imported to the farm from conventional animal agriculture sources, given the relative scale of the conventional and organic livestock sectors in Canada. Manure contains N-P-K nutrients from synthetic fertilizers that were originally applied to a conventional crop that are then recycled for organic production. Therefore, the manure was assumed to be a co-product of conventional livestock production, and was treated as a recycled product given its use in the organic field crop system (Leip et al., 2019). Nutrient recycling is considered a potential strategy to reduce environmental impacts from agricultural systems (Kytta et al., 2021). Thus, instead of using allocation of impacts between the livestock and manure, only the impact of the nutrient supply is considered. The impacts of the nutrients are divided equally, known as the 50/50 method (Lee & Inaba, 2004). The 50/50 method assumes that “the environmental loads of the recycling of material from one production system to another are shared equally between two adjacent production systems” (Lee & Inaba, 2004), in this analysis, those product systems are the conventional feed crop and organic field crop system. Applying this method, 50% of the upstream environmental impacts associated with the fertilizer production of N, P, and K fraction supplied by manure are allocated to the organic crop production, while 50% are allocated to the conventional feed crop production system, that is fed to the livestock to produce manure (Figure 3-4). The justification of a 50/50 allocation of upstream industrial fertilizer production impacts is based on the following:

> *"if the market shows no visible disequilibrium (lack of secondary raw materials [...]), then the advantage should be split equally between the producer using the recycled material and the producer producing a recycled product: 50/50 allocation split"* (AFNOR, 2011, p. 19)

The types of fertilizers used to represent the nutrients from conventional crop production that are present in the manure were based on Canadian fertilizer consumption from 1961-2019, found through the International Fertilizer Association (IFA, 2022). These include: 1) for total N: liquid anhydrous ammonia, ammonium nitrate, ammonium sulfate, calcium ammonium nitrate, and urea; 2) for total P_2O_5: single superphosphate, triple superphosphate; and 3) for total K_2O: potassium chloride and potassium sulphate. Details of the IFA report for average Canadian fertilizer consumption can be found in Appendix L. The processes and providers chosen from ecoinvent are shown in Appendix H.

It was assumed that manure was transported from its source to the farm using freight transport by lorry (7.5 to 16 metric tonne) over a distance of 8 km, based on average distances provided in: 1) a Saskatchewan study by Nagy and colleagues (1999) that found manure is hauled distances between 1 and 7.9 km; and 2) an Alberta study by Toma and Bouma Management Consultants (2006) that found manure is hauled between 4.99 and 18.83 km.



Industrial manufacturing processes create inorganic fertilizer that is sent to conventional farms for use

The N-P-K in inorganic fertilizers made from industrial processes grow conventional crops for feed

The conventional crops feed animals, which in turn produce nutrient-rich manure

The nutrient-rich manure is full of N-P-K which can be used to help grow organic crops

The organic crops grow with help from the nutrients from the manure

With 50/50 allocation, 50% of the impacts associated with the manure are allocated to conventional crop production

Since the N-P-K in manure originated from industrial inorganic fertilizer that helped to grow conventional crops, impacts of the manure should be split between the conventional and organic cropping systems

With 50/50 allocation, 50% of the impacts associated with the manure are allocated to organic crop production

Industrial manufacturing of inorganic fertilizers

Organic crop production

This analysis cuts out the conventional crop and animal production steps by modelling all manure inputs as coming from the industrial manufacturing of inorganic fertilizers. The 50/50 allocation is applied so that only 50% of manure impacts are accounted for while the other 50% are still assumed to be allocated to the conventional crop production (not modelled).

Figure 3-4 50/50 allocation methodology demonstrating the proportion of upstream impacts from the production of inorganic N, P, and K assigned to the production of the conventional feed (50%) and the organic field crop (50%).

3.3.2.4.1.2 Green Manures and Cover Crops

For farms that practiced rotations with another crop or multiple crops (i.e., a crop rotation, intercropping, green manures/leguminous crops, or cover crops), these crops were modeled separately. Several green manures (alfalfa, clover, lentils, and peas) were identified by producers as being grown in conjunction with their field crops. However, not all producers provided full life cycle inventory data on their green manure growth (i.e., seeded area, seeding rate, method of incorporation, etc.). Therefore, full life cycle inventory sets for alfalfa, clover, lentils, and peas that were provided by producers were extrapolated and applied for all instances where the respective green manure was grown. For clover, lentils, and peas, only one full life cycle inventory data set each was provided by producers so these crop-specific LCI datasets were applied where ever these same crops were grown as a green manure in another farm's rotation. For alfalfa, one LCI dataset was provided by a farmer. These LCI inputs were averaged to create one 'typical' or average alfalfa production model which was used to characterize the LCI of all instances where alfalfa was grown as a green manure in a rotation for which data were missing. All of these stand-in green manure production models were used as is, except for scaling their LCI data up to down in proportion to the land area to which they were to be applied relative to the land area over which they were originally applied.

Green manures are grown in part to contribute to nitrogen needs of the subsequent crops in rotation, via biological nitrogen fixation, and are then incorporated into the soil. Therefore, the impacts from their production (i.e. associated with all material and energy inputs, and all emissions from soil) were allocated to subsequent crops in the rotation based on the total nitrogen content of the subsequent harvested crops. There were no additional nitrogen sources provided to the subsequent crops. Figure 3-5 illustrates the nitrogen allocation methodology with a mock crop rotation.

There is considerable uncertainty regarding the LCI dataset of green manures grown in select crop rotations. Given one full LCI dataset provided for the green manure, red clover, from Quebec, using it as a proxy for Ontario red clover crop is potentially inappropriate and perhaps misrepresents its true environmental impact. Using these limited LCI datasets as a representative of all green manure production is associated with potentially high uncertainty, particularly in terms of how geographic setting might impact green manure yields. Uncertainties concerning accurate representation of green manures in both in Ontario and Quebec are addressed by assuming a standard yield of 2 t ha^{-1} (Thiagarajan et al., 2018) and provincial seeding rates coupled with farmer LCI data to create a representative, but general, green manure model. In addition, 2 t ha^{-1} was used to ensure modelling of green manures were consistent across above- and belowground residues calculations and Holos modeling of soil organic carbon changes.

One major assumption made was that green manure impacts were allocated to subsequent crops in rotation in proportion to the nitrogen content of those harvested crops. This assumption has impacts on nitrogen emissions and subsequent life cycle impacts. It is also associated with uncertainty. Consequently, a sensitivity analysis was performed on this parameter to test the model's sensitivity to the GM allocation methodology. Instead of allocating GM impacts to “X” number of subsequent crops in the rotation after a green manure or leguminous crop, until the next green manure or leguminous crop was grown (as illustrated in Figure 3-6), 100% of GM or leguminous crop impacts were placed solely on the succeeding crop. This is similar to the methodology used by Styles et al. (2015) where burdens of crop residues were allocated exclusively to the subsequent crop grown in rotation (Jeswani et al. 2018). There is an exception for leguminous crops that are grown to produce a harvestable crop (e.g. soybeans). Impacts were still split on a nitrogen basis between the green manure/leguminous crop and the next crop, but not between other crops in the rotation.

Similar to the green manures, cover crop LCI information was not provided. However, producers did provide information on how their cover crops were incorporated. Therefore, a single rye LCI dataset was assumed to represent all cover crop growth (since rye was the only cover crop identified) with farm-specific methods of incorporation. Legume cover crops are effective at nitrogen fixation, while rye cover crops suppress weeds, increase water availability, slow erosion, control pests, immobilize N, and provide N-rich biomass that is available to the subsequent crop if left on the field to decompose or incorporated into the soil (Wayman et al., 2016; Kessavalou & Walters, 1999; Clark, 2015; Government of Ontario, 2016; United States Department of Agriculture; 2022). Thus, it is assumed that 100% of the available nitrogen provided by the cover crop is allocated to the subsequent crop in rotation and does not remain available to further crops in rotation. Furthermore, 100% of the upstream environmental impacts from the rye cover crops were allocated entirely to the subsequent crop in the rotation because it was assumed that the benefits of the cover crop were solely being delivered only to the subsequent crop.

For leguminous crops grown in rotation that also yielded a harvested component (e.g. soybeans), the co-product was the fixed nitrogen in the soil, which could be used by subsequent crops. The soybean crop was modeled based on the nitrogen content of the field crop plant fractions, including the above- and below-ground residues and harvestable crop, provided by Thiagarajan et al. (2018) and Janzen et al. (2003). Then, a two-step allocation process was adopted. First, all soil emission and life cycle impacts arising from growing the harvested leguminous crop were allocated initially between a) the harvested grain portion of their biomass, and b) the combined above- and below-ground residues of these plants in proportion to the nitrogen content of these plant fractions (See Figure 3-6 and Appendix N). Second, the impacts associated with the below- and above-ground biomass portions of harvested leguminous crops, effectively the portions of the plants left to decompose in the field, were then allocated to subsequent crops grown in the rotation in proportion to the nitrogen, as shown in Figure 3-6. As a result, 19.8% of soil emissions and life cycle impacts from the leguminous crop were allocated to subsequent crops in rotation (until the next leguminous crop) while 80.2% was retained by the harvested legume.

All data pertaining to field crop plant fractions (i.e. above- and below-ground residues and harvestable crop) was provided by Thiagarajan et al. (2018) and Janzen et al. (2003). Data on wet to dry weight conversions for various field crops were taken from Feedipedia (2022) and California Certified Organic Farming (2022).

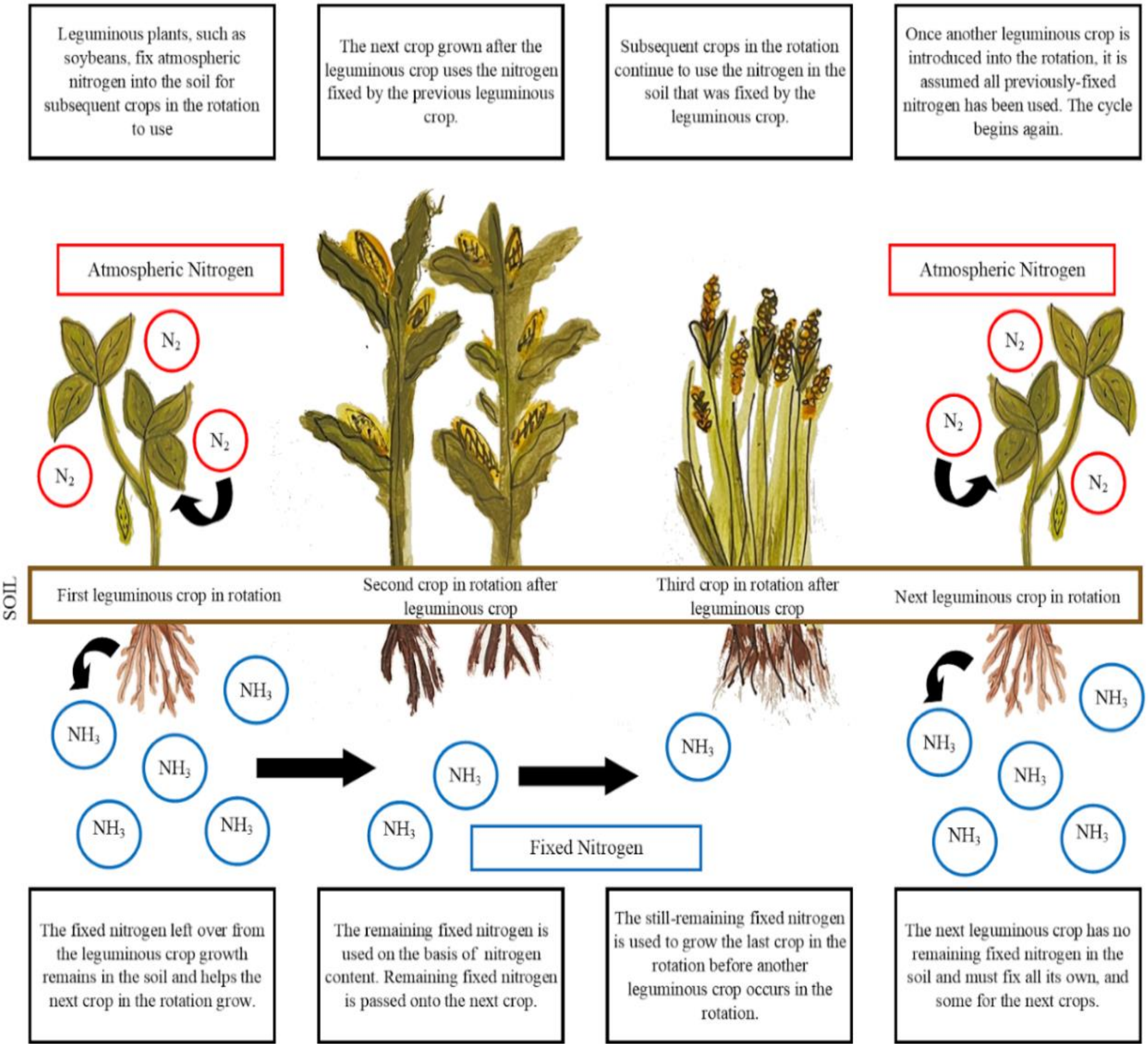
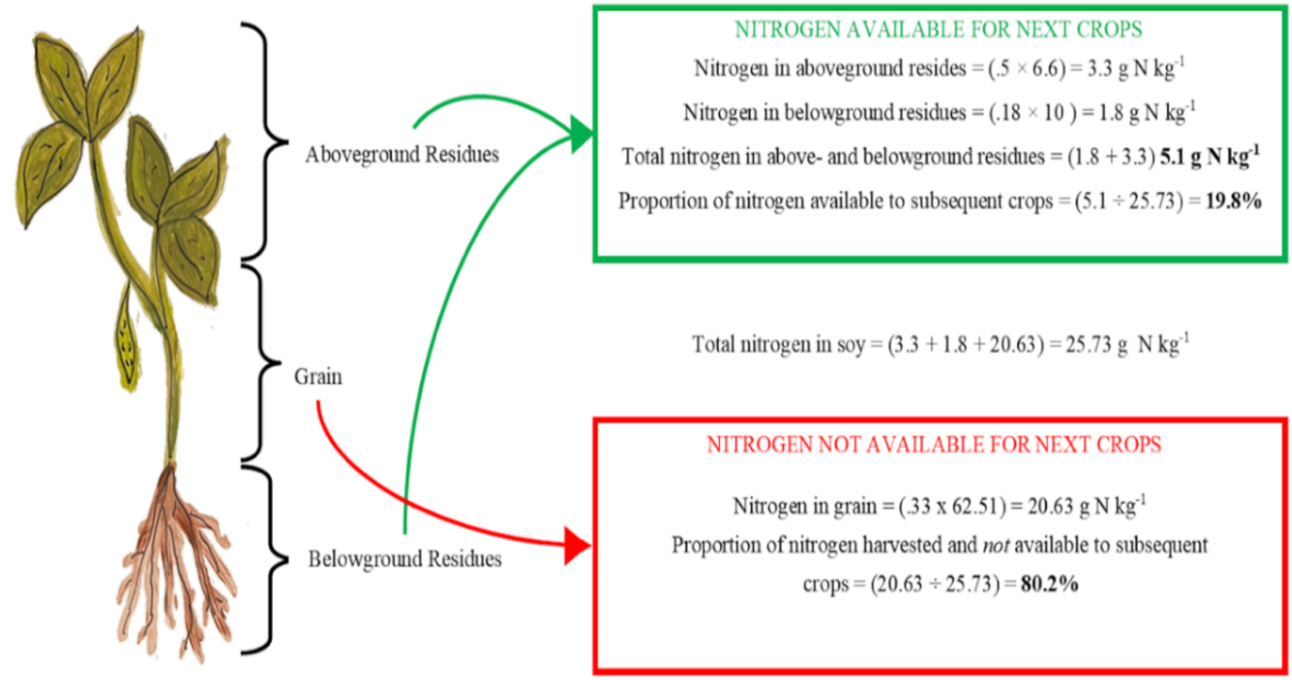


Figure 3-5 Allocation of nitrogen fixed by a leguminous crop is shown through a soybean-corn-wheat rotation.

Crop	N Concentration (g N kg^{-1}; dry matter basis) in grain	N Concentration (g N kg^{-1}; dry matter basis) in aboveground residues	N Concentration (g N kg^{-1}; dry matter basis) in belowground residues	Calculated plant partitioning of total plant dry matter into grain (%) (G=2t ha^{-1})	Calculated plant partitioning of total plant dry matter into aboveground residues (%) (G=2t ha^{-1})	Calculated plant partitioning of total plant dry matter into belowground residues (%) (G=2t ha^{-1})
Soy	62.51	6.6	10	33	50	18



NITROGEN AVAILABLE FOR NEXT CROPS

Nitrogen in aboveground resides = (.5 × 6.6) = 3.3 g N kg^{-1}

Nitrogen in belowground residues = (.18 × 10) = 1.8 g N kg^{-1}

Total nitrogen in above- and belowground residues = (1.8 + 3.3) **5.1 g N kg^{-1}**

Proportion of nitrogen available to subsequent crops = (5.1 ÷ 25.73) = **19.8%**

Total nitrogen in soy = (3.3 + 1.8 + 20.63) = 25.73 g N kg^{-1}

NITROGEN NOT AVAILABLE FOR NEXT CROPS

Nitrogen in grain = (.33 x 62.51) = 20.63 g N kg^{-1}

Proportion of nitrogen harvested and *not* available to subsequent crops = (20.63 ÷ 25.73) = **80.2%**

Crops are portioned into aboveground residues, belowground residues, and grain. Each portion has a different nitrogen concentration.

In crops with a yield, like this soy, the grain portion is taken off the field and the nitrogen in the grain is not available to the next crops in the rotation.

The amount of nitrogen available to the next crops in rotation is found by summing the nitrogen contents of the above– and belowground residues: since these portions of the crop are left on the field.

Using Thiagarajan et al. (2018) values as a reference, we know that 5.1 g (19.8%) of nitrogen is available to be allocated to the subsequent crops in the rotation, while 20.63 g (80.2%) of nitrogen is taken off the field during harvest and unavailable.

Figure 3-6 Two-step process of allocating soil emissions and life cycle environmental impacts resulting from leguminous crops where a harvest occurs between that crop and subsequent crops are grown in rotation.

3.3.2.4.2 Modeling Soil-level Emissions

Direct and indirect emissions arising from N application (i.e. nitrous oxide, ammonia, nitrogen oxide, and nitrate) were estimated using the Intergovernmental Panel on Climate Change (IPCC) Tier 2 methodology for agriculture, forestry, and other land use, the National Inventory Report (NIR) 1990-2020: Greenhouse gas emission sources and sinks in Canada, and the Carbon Footprints for Major Canadian Grains Methodology Report (CRSC, 2017; Environment and Climate Change Canada, 2022; IPCC, 2006). Phosphorus (P) emissions were adopted from the SALCA-P methodology (Prasuhn, 2006) developed by Agroscope. An example of each calculation using farmer-provided life cycle inventory data for the organic production of rye in Ontario appears in Appendix M. All calculations were performed on a per functional unit (1 t crop harvested) basis.

Finally, changes in SOC were modeled using Holos software. The best approach to modeling these is to do it based on local agro-climatic conditions. Since latitude and longitude positions of each farm were collected, they were used to align farm locations within Reconciliation Units (RU). The RU reconciles Canadian ecozones and provincial/territorial borders, and is the smallest geographical unit for which results are computed in this study (Figure 3-7).

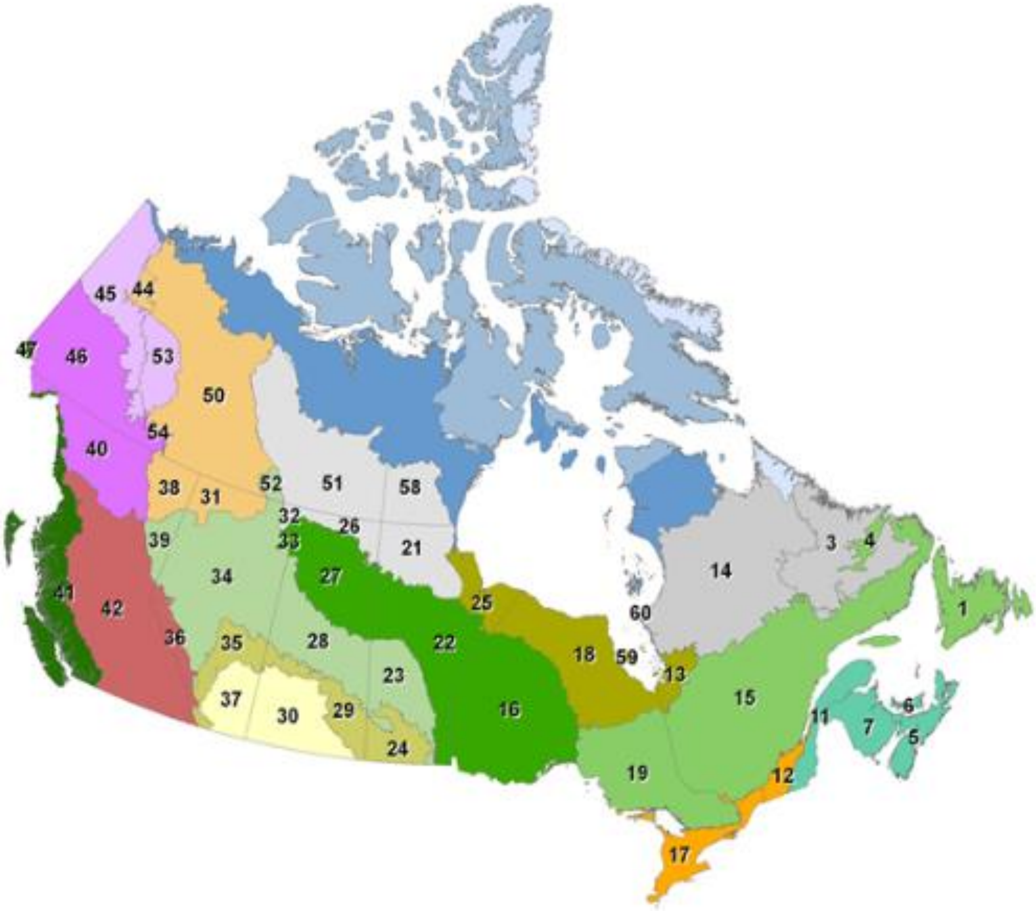


Figure 3-7 The reconciliation unit map of Canada created by Natural Resources Canada (2011) is used to "ensure consistency of data from multiple agencies during the development of estimates" and is the smallest unit for which results are compared in this analysis.

3.3.2.4.2.1 Annual Direct N_2O-N Emissions

Direct nitrous oxide (N_2O) emissions are a result of denitrification of applied nitrogen, and occurs in anaerobic conditions. Annual direct N_2O emissions for organically managed soils are determined using the following equation:

$$\text{Equation 1) } N_2O\text{-}N = (F_{on} \times EF_1F_{on}) + (F_{cr} \times EF_2F_{cr}) + (F_{som} \times EF\ F_{som})$$

Where

- $N_2O\text{-}N$ = annual direct $N_2O\text{-}N$ emissions from N inputs to managed soils (kg $N_2O\text{-}N$ yr^{-1})
    - Note: this value is in units of kg N_2O as N yr^{-1}. To convert this unit to kg N_2O yr^{-1}, the final solution of Equation 1 is multiplied by the molecular mass ratio of N_2O to N (i.e., mass of $N_2O\text{-}N \times (44 \div 28)$ = mass of N_2O)
- F_{on} = annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1}) (Equation 1.7)
- F_{cr} = annual amount of N in crop residues (above-ground and below ground), returned to soils (kg N yr^{-1}) (Equation 1.7)
- F_{som} = the net annual amount of N mineralized in mineral soils as a result of loss of soil carbon through change in land use or management (kg N yr^{-1}) (Equation 1.8)
- EF_1F_{on} = emissions factor for organic nitrogen lost as N_2O following application to agricultural soils (kg $N_2O\text{-}N$ per kg N applied)
- EF_2 F_{cr} = emissions factor for crop residue nitrogen lost as N_2O following application to agricultural soils (kg $N_2O\text{-}N$ per kg N applied)
- EF_1 F_{som} = emission factor for N additions from mineral fertilizers, organic amendments and crop residues, and N mineralized from mineral soil as a result of loss of soil carbon (kg N_2O-N per kg N applied)

Values for EF_1F_{on} and EF_2F_{cr} were both found in the Canadian National Inventory Report Part 2 Table A6.4-20 (Environment and Climate Change Canada, 2022). The value for EF_1 F_{som} is not defined by any source. EF_1 is defined by Hergoualc'h et al. (2021) as an emission factor for N_2O "from fertilizer application, crop residues returned to soils, and decomposition of soil organic matter of mineral soils" (p. 2) and defined by the IPCC (2006) "for N additions from mineral fertilizers, organic amendments and crop residues, and N mineralized from mineral soil as a result of loss of soil carbon" (p. 11). Therefore, the same emission factors (EF_1) associated F_{on} are used as the emissions factors for F_{som} (i.e. EF_1F_{som}). Considering that F_{som} requires an emission factor for Equation 1, the absence of published emission factors for 'F_{som}', and the definition of all emission factors for direct N_2O, it was assumed that the emission factors associated with F_{on} could be used as the soil organic matter (F_{som}) emission factor.

The F_{on} values were calculated by summing the nutrients (where applicable) applied to a crop, multiplied by the nitrogen (N) content of the nutrient application (Equation 1.1).

$$Equation\ 1.1)\ F_{Amendments} = [(A_1 \times N_{Amendmens1}) + (A_2 \times N_{Amendment2})... + (A_X \times N_{AmendmentX})]$$

Where:

- $F_{amendments}$ = total nitrogen content of manures and organic amendments applied (kg N t^{-1})
- A_1 = amount of first manure or organic amendment applied to crop (kg N t^{-1}) (from farm inventory data)
- $N_{Amendment1}$ = nitrogen content of amendment 1 (%)
- A_2 = amount of second manure or organic amendment applied to crop (kg N t^{-1}) (from farm inventory data)
- $N_{Amendment2}$ = nitrogen content of amendment 2 (%)
- A_x = additional amount of manures or organic amendments applied to crop (kg N t^{-1}) (from farm inventory data)
- $N_{AmendmentX}$ = nitrogen content of additional amendments applied to crop (%)

Representative nitrogen contents of manure and other nutrient sources were derived from various sources and can be found in Appendix C and Appendix D, respectively.

In addition to manures and organic nutrient applications, green manures and residual nitrogen content from nitrogen fixing crops in a rotation were included in the F_{on} value. Green manure nitrogen content was calculated based on the following Equation 1.2:

$$Equation\ 1.2)\ F_{NitrogenGM} = [(DM_G \times N_G) + (DM_{AGR} \times N_{AGR}) + (DM_{BGR} \times N_{BGR})] \times (Y \div 1000)$$

Where

- $F_{NitrogenGM}$ = kilograms of nitrogen per hectare from green manures and cover crops that will be divided between subsequent crops in a crop rotation using Equation 1.3 (kg N ha^{-1})
- Y = yield (if applicable) (kg N ha^{-1}) (from farm inventory data)
- DM_G = typical grain dry matter fraction (%) (CCOF, 2015; Feedipedia, 2022)
- N_G, N_{AGR}, N_{BGR} = nitrogen content of the grain, aboveground, and belowground residue fractions of the green manure crop (g N kg^{-1}) (Thiagarajan et al., 2018; Janzen et al., 2003)

- G_{DM}, AGR_{DM}, BGR_{DM} = grain, aboveground residue, and belowground residue fractions of total plant dry matter (% of DM) (Thiagarajan et al., 2018; Janzen et al., 2003)

Since some leguminous crops that were grown in some rotation had their grain fraction harvested (e.g. soybeans), only the nitrogen fraction for the aboveground and belowground portions (as illustrated in Figure 3-6) were considered as being available to the subsequent crops in the rotation as follows (Equation 1.2.1):

$$\text{Equation 1.2.1)}\ F_{NitrogenL} = [(DM_{AGR} \times N_{AGR}) + (DM_{BGR} \times N_{BGR})]\ \ (Y \div 1000\ )$$

Where

- $F_{NitrogenL}$ = N from leguminous crops with a harvest that will be divided between subsequent crops in a crop rotation using Equation 1.3.1 (kg N ha^{-1})
- All other variables are the same as in Equation 1.2

From the nitrogen content of green manures and cover crops, the fraction of N inputs and upstream environmental impacts that are allocated to the subsequent crop(s) in a rotation until the next green manure or leguminous crop is grown (see Figure 3-5) was determined with Equation 1.3:

$$\text{Equation 1.3)}\ F_{NFractionGM} = N_{crop1} \div [N_{crop1} + N_{crop2} + \ldots N_{cropX}]$$

Where

- $F_{NFractionGM}$ = the fraction biologically fixed nitrogen inputs from prior green manures or cover crops grown that are assumed to accrue from growing a subsequent crop of interest in the rotation (%)
- N_{crop1} = total nitrogen content of green manure (t N ha^{-1}) (derived from Equation 1.2)
- N_{crop2} = the total nitrogen content of the crop after the green manure in rotation (t N ha^{-1}) (derived from Equation 1.2)
- N_{cropX} = nitrogen content of last crop in rotation before another green manure (t N ha^{-1}) (derived from Equation 1.2)

Due to the harvesting of the grain portion of leguminous crops, the fraction of N inputs and emissions from leguminous crops with a harvest is found using Equation 1.3.1:

$$Equation\ 1.3.1)\ F_{NFractionL} = N_{crop1} \div [N_{crop1} + N_{crop2} + \ldots N_{cropX}]$$

Where

- $F_{NFractionL}$ = the fraction of biologically fixed nitrogen inputs and emissions from prior green manures or cover crops that are assumed to accrue from growing a subsequent crop of interested in the rotation (%)
- N_{crop1} = total nitrogen content of the crop grown immediately after the leguminous crop with a harvest (t N ha^{-1}) (derived from Equation 1.2.1)
- N_{crop2} = the total nitrogen content of the crop grown next in the rotation (t N ha^{-1}) (derived from Equation 1.2.1)
- N_{cropX} = nitrogen content of last crop in rotation before another leguminous crop (t N ha^{-1}) (derived from Equation 1.2.1)

The outputs of Equation 1.3.1 for one rotation will sum to 100%, similarly to Equation 1.3 (see N Emissions Calculation Example, Appendix M). However, in Equation 1.3.1 it should be noted that the 100% summation does not refer to allocating 100% of nitrogen and hence, all related soil and upstream life cycle environmental impacts of the harvested leguminous crop to the subsequent crops in the rotation. Rather, only the aboveground and belowground portion of nitrogen (and the proportionate environmental impacts) are allocated to subsequent crops in the rotation: as illustrated in Figure 3-6 with a soy crop.

To determine the amount of nitrogen that is available from the green manures to be allocated to subsequent crops, Equation 1.4 is used:

$$Equation\ 1.4)\ Nitrogen_{GM} = [2000 \times (N_G \div 1000)] + [(2000 \div G_{DM}) \times AGR_{DM} \times (N_{AGR} \div 1000)] + [(2000 \div G_{DM}) \times BGR_{DM} \times (N_{BGR} \div 1000)]$$

Where

- $Nitrogen_{GM}$ = total nitrogen available from the green manures to be allocated (kg N ha^{-1})
- 2000 = assumed dry matter grain yield of 2 t ha^{-1} (Thiagarajan et al., 2018)
- DM_G = typical grain dry matter fraction (%) (CCOF, 2015; Feedipedia, 2022)

- N_G, N_{AGR}, N_{BGR} = nitrogen content of the grain, aboveground, and belowground residue fractions of the green manure crop (g N kg^{-1}) (Thiagarajan et al., 2018; Janzen et al., 2003)
- G_{DM}, AGR_{DM}, BGR_{DM} = grain, aboveground residue, and belowground residue fractions of total plant dry matter (% of DM) (Thiagarajan et al., 2018; Janzen et al., 2003)

Sources for calculated plant partitioning of total plant dry matter (DM) into aboveground residue (AGR), belowground residue (BGR), and grain (G); and percent nitrogen of crop residues are found in Thiagarajan et al. (2018) and Janzen et al. (2003). A table of these values and their sources is located in Appendix N. While Thiagarajan et al. (2018) and Janzen et al. (2003) were able to provide values for the majority of crops, several proxies had to be used, still using the Thiagarajan et al. (2018) and Janzen et al. (2003) figures, below is a list of proxies:

- Tame hay (alfalfa & mix) values in place of clover,
- Wheat values in place of spelt, and
- Vegetable values in place of radish.

Leguminous crops with a harvest are treated slightly differently from green manures with no harvest. Determining available nitrogen that can be allocated to subsequent crops is done using Equation 1.4.1:

$$\text{Equation 1.4.1)}\ Nitrogen_L = [(AGR_{DM} \div G_{DM}) \times (N_{AGR} \div 1000) \times DM_G \times Y] + [(BGR_{DM} \div G_{DM}) \times (N_{BGR} \div 1000) \times DM \times Y]$$

Where

- $Nitrogen_L$ = total nitrogen available from the leguminous crops with a harvest to be allocated (kg N ha^{-1})
- Y= yield of leguminous crop with a harvest (kg ha^{-1}) (derived from crop inventory data)
- DM_G = typical grain dry matter fraction (%) (CCOF, 2015; Feedipedia, 2022)
- N_{AGR}, N_{BGR} = nitrogen content of the aboveground and belowground residue fractions of the leguminous crop (g N kg^{-1}) (Thiagarajan et al., 2018; Janzen et al., 2003)
- G_{DM}, AGR_{DM}, BGR_{DM} = grain, aboveground residue, and belowground residue fractions of total plant dry matter (% of DM) (Thiagarajan et al., 2018; Janzen et al., 2003)

The resulting percentage of the Nitrogen_{GM} or Nitrogen_{L} equation (Equation 1.4 or Equation 1.4.1) is then multiplied by the results of Equation 1.3 (or Equation 1.3.1) to get a total kg N ha^{-1} derived from a green manure or leguminous crop that is contributing to the subsequent crop in the rotation. This operation is shown below in Equation 1.5:

$$\textit{Equation 1.5)}\ F_{TotalGM} = F_{NitrogenGM} \times Nitrogen_{GM}$$

or

$$F_{TotalL} = F_{NitrogenL} \times Nitrogen_{L}$$

Where

- $F_{TotalGM}$ = total nitrogen from green manure allocated to the subsequent crop in rotation on a land area basis (kg N ha^{-1})
- Nitrogen_{GM} = total nitrogen available from the green manures to be allocated (kg N ha^{-1}) (from Equation 1.4)
- $F_{NFractionGM}$ = the fraction of nitrogen inputs and emissions from prior green manures or cover crops grown (%) (from Equation 1.3)

And

- F_{TotalL} = total nitrogen from leguminous crop with a harvest allocated to the subsequent crop in rotation on a land area basis (kg N ha^{-1})
- Nitrogen_{L} = total nitrogen available from the leguminous crops with a harvest to be allocated (kg N ha^{-1}) (from Equation 1.3.1)
- $F_{NFractionL}$ = the fraction of nitrogen inputs and emissions from prior leguminous crop grown (%) (from Equation 1.4.1)

To convert the nitrogen contributions derived from a green manure or leguminous crop that are deemed to have been used by a crop of interest from kg ha^{-1} to a functional unit basis (kg t^{-1} harvested crop), solutions from Equations 1.5 are substituted into Equation 1.6:

$$\textit{Equation 1.6)}\ F_{TotalFU} = F_{Total} \div (Y \div 1000)$$

Where

- $F_{TotalFU}$ = fraction of nitrogen from leguminous crop or green manure allocated to the subsequent crop in rotation on a functional unit basis (kg N t^{-1})
- F_{Total} = fraction of nitrogen from leguminous crop or green manure allocated to the subsequent crop in rotation on a land area basis (kg N ha^{-1}) (from Equation 1.5)
- Y = yield of the subsequent crop in rotation (kg ha^{-1}) (from crop inventory)

The resulting values of Equation 1.6, in addition to the nitrogen fraction from organic amendments (Equation 1.1), are added together and result in F_{on}: the variable from Equation 1. This operation is shown with Equation 1.7 below:

$$\textit{Equation 1.7)}\ F_{on} = F_{TotalFU} + F_{Amemdments}$$

Where

- F_{on} = annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1})
- $F_{TotalFU}$ = fraction of nitrogen from leguminous crop or green manure allocated to the subsequent crop in rotation on a functional unit basis (kg N t^{-1}) (from Equation 1.6)
- $F_{Amendments}$ = total nitrogen content of manures and organic amendments applied (kg N t^{-1}) (from Equation 1.1)

In the case of a green manure that is grown on the same field at the same time as a crop, this is treated as a rotation with the green manure being grown first. The same allocation calculations apply. Since cover crops are primarily planted for soil health, erosion mitigation, and weed control (Clark, 2008; Dabney et al., 2001; Kaspar and Singer, 2011; Reeves, 1994) rather than fixing nitrogen, the environmental impacts of cover crops grown in conjunction with another crop are placed solely on that one crop. Similarly, nitrogen impacts of manure and other nutrient applications are deemed to benefit, and hence, their impacts are allocated entirely to the crop being grown at the time. This is because it is assumed that producers are practicing precision nutrient management, and therefore only applying the necessary manure, nutrients, and subsequent nitrogen to support the crop to which it is directly applied (Agriculture and Agri-Food Canada, 2022b; Ess et al., 2001; Hedley, 2015; Patil, 2009).

F_{cr} values used in Equation 1 were determined using Equation 1.8:

$$\text{Equation 1.8)}\ F_{cr} = [(BGR_{\%\ of\ DM} \div G_{\%\ of\ DM}) \times N_{BGR} \times DM_{crop}] + [(AGR_{\%\ of\ DM} \div G_{\%\ of\ DM}) \times N_{AGR} \times DM_{crop}]$$

Where

- F_{cr} = annual amount of N in crop residues (above-ground and below ground), returned to soils (kg N yr^{-1})
- $BGR_{\%\ of\ DM}$ = partitioning of total plant dry matter (DM) into belowground residue for entire crop rooting depth (Thiagarajan et al., 2018, Table 3)
- $G_{\%\ of\ DM}$ = plant partitioning of total plant dry matter into grain (Thiagarajan et al., 2018, Table 3)
- N_{BGR} = N concentration of belowground residue (g N kg^{-1}) (Thiagarajan et al., 2018 Table 2)
- DM_{crop} = dry matter of crop residues at harvest (%), from nutritional tables in Feedipedia (Feedipedia, 2020) (dry matter, aerial (fresh) from Feedipedia used as most accurate harvest dry matters. Dry matter ranges at harvest confirmed through sources in Appendix N)
- $AGR_{\%\ of\ DM}$ = partitioning of total plant dry matter into aboveground residue (Thiagarajan et al., 2018, Table 3)
- N_{AGR} = N concentration of aboveground residue (g N kg^{-1}) (Thiagarajan et al., 2018, Table 2)

Gaps in the Thiagarajan et al. (2018) tables were filled with values from Janzen et al. (2003) and summarized in Appendix N. However, since not all crops of interest were available in the Thiagarajan et al. (2018) or Janzen et al. (2003) tables, several proxy substitutions were made for dry matter partitioning and N concentrations of above and belowground residues. Those substitutions are as follows:

- Wheat values from Thiagarajan et al. (2018) in place of spelt,
- Barley values from Thiagarajan et al. (2018) in place of rye,
- Tame hay (alfalfa & mix) values from Janzen et al. (2003) in place of clover and perennial grass, and
- Oat values from Janzen et al. (2003) in place of hay and smooth bromegrass.

The corresponding dry matter content of each crop residue was still applied despite the use of proxies for dry matter partitioning and N concentrations of above and belowground residues.

The F_{som} values used in Equation 1 represent the mineralization of nitrogen from soils undergoing loss of soil organic matter. As such, it only arises in this analysis where soils were found to be losing soil organic carbon to the atmosphere based on the results of the Holos modeling. The F_{som} values were found using the IPCC 2006, Ch. 11 equation 11.8, here known as Equation 1.9:

$$\textit{Equation 1.9)}\ F_{som} = \sum_{LU}[(\Delta C_{mineral,\,LU} \times (1 \div R) \times 1000]$$

Where

- F_{som} = the net annual amount of N mineralized in mineral soils as a result of loss of soil carbon through change in land use or management (kg N)
- $C_{mineral,\,LU}$ = average annual loss of soil carbon for each land management practice (Mg C ha^{-1}) (from Holos modelling output, Agriculture and Agri-Food Canada, 2022c)
- R = C:N ratio of the soil organic matter (deemed to be 11:1, see below for discussion)
- LU = land-use and/or management system type

In this analysis, the C:N ratio of the soil organic matter (R) is 11 for all soil types. This value comes from the National Inventory Report (NIR), part 2 (2022) stating that “A database containing soil organic carbon (SOC) and N for all major soils in Saskatchewan (a data set of about 600) was used to derive an average C:N ratio of 11 with a standard deviation of 1.9. The C:N ratio of agricultural soils is considered to be consistent among regions” (p. 133). Furthermore, this value of 11 falls within the IPCC 2006 C:N ratio guidelines, which propose a C:N ratio range from 8-15. Values for $\Delta C_{mineral,\,LU}$ were taken directly from the Holos soil organic carbon modeling.

3.3.2.4.2.2 Annual Indirect N_2O-N Emissions

The IPCC’s NIR identifies indirect N_2O emissions from volatilization as those emissions “from atmospheric deposition of N volatilised from managed soils” (IPCC, 2006, p. 21). The indirect N_2O volatilization for organically managed soils in calculated in Equation 2:

$$\textit{Equation 2)}\ N_2O_{[ATD]}\text{-}N = (F_{on} \times Frac_{gasm}) \times EF_4$$

Where

- $N_2O_{[ATD]}$-N = annual amount of N_2O-N produced from atmospheric deposition of N volatilized from organically managed soils (kg N_2O-N yr^{-1})
    - Note: this value is in units of kg $N_2O_{[ATD]}$ as N yr^{-1}. To convert this unit to kg N_2O yr^{-1}, the final solution of Equation 2 is multiplied by the molecular mass ratio of N_2O to N of (44 ÷ 28 kg N_2O kg^{-1} N_2O-N)
- F_{on} = annual amount of managed animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1}) (derived from Equation 1.7)
- $Frac_{gasm}$ = fraction of applied organic N fertilizer materials (F_{on}) that volatilizes as NH_3 and NO_x [kg N volatilized (kg of N applied of deposited)$^{-1}$] (from NIR Part 2, Table A6.4-21)
- EF_4 = emissions factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces [kg N_2O-N (kg NH_3-N + NO_x-N volatilized)$^{-1}$] (from NIR Part 2, Table A6.4-22)

Equations for NO_x produced and NH_3 produced are found using Equations 2.1 and 2.2, respectively.

$$\textit{Equation 2.1)}\ NO_x\ \textit{produced} = (F_{on} \times Frac_{gasm}) \times 0.1$$

Where

- NO_x produced = annual amount of nitrogen oxide emissions to air (kg NO_x)
    - Note: this value is in units of kg NO_x as N yr^{-1}. To convert this unit to kg NO_x yr^{-1}, the final solution of Equation 2.1 is multiplied by the molecular mass ratio of NO_x to N (46÷14 kg NO_x kg^{-1} NO_x-N) (US EPA, 2021)
- F_{on} = annual amount of managed animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1}) (derived from Equation 1.7)
- $Frac_{gasm}$ = fraction of applied organic N fertilizer materials (F_{on}) that volatilizes as NH_3 and NO_x [kg N volatilized (kg of N applied of deposited)$^{-1}$] (from NIR Part 2, Table A6.4-21)
- 0.1 = Proportion of N volatilized as NO_x (Brentrup et al., 2000)

In calculating the amount of NO_x produced (Equation 2.1) a molecular mass was needed to convert NO_x-N to NO_2. To simplify this equation, a single molecular mass was chosen to represent all nitrogen oxides (NO_x), despite nitrogen oxide being made up of nitrous oxide (NO_2) and nitrogen oxide (NO) (US EPA, 2021). Therefore, the molecular weight of nitrous oxide (44 g mol^{-1}) was used for all nitrogen oxide conversions. This is due to the “fast rate of transformation of NO to NO_2 under ambient conditions” (US EPA, 2021).

$$\textit{Equation 2.2)}\ NH_3\ produced = (F_{on} \times Frac_{gasm}) \times 0.9$$

Where

- NH_3 produced = annual amount of ammonia emissions to air (kg NH_3)
    - Note: this value is in units of kg NH_3 as N yr^{-1}. To convert this unit to kg NH_3 yr^{-1}, the final solution of Equation 2.2 is multiplied by the molecular mass ratio of NH_3 to N of (17 ÷ 14 kg NH_3 kg^{-1} NH_3-N)
- F_{on} = annual among of managed animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1}) (derived from Equation 1.7)
- $Frac_{gasm}$ = fraction of applied organic N fertilizer materials (F_{on}) that volatilizes as NH_3 and NO_x [kg N volatilized (kg of N applied of deposited)$^{-1}$] (from NIR Part 2, Table A6.4-21)
- 0.9 = Proportion of N volatilized as NH_3 (Brentrup et al., 2000)

Indirect nitrogen emissions from leaching and runoff are calculated with Equation 3, detailed below:

$$\textit{Equation 3)}\ N_2O_{[L]}\text{-}N = (F_{on} + F_{cr} + F_{som}) \times\ Frac_{leach\text{-}[H]} \times EF_5$$

Where

- $N_2O_{[L]}$-N = annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs (kg N2O–N yr^{-1})
    - Note: this value is in units of kg $N_2O_{[L]}$ as N yr^{-1}. To convert this unit to kg N_2O yr^{-1}, the final solution of Equation 3 is multiplied by the molecular mass ratio of N_2O to N of (44 ÷ 28 kg N_2O kg^{-1} N_2O-N)

- F_{on} = annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1}) (Equation 1.2)
- F_{cr} = annual amount of N in crop residues (above-ground and below ground), returned to soils (kg N yr^{-1}) (Equation 1.4)
- F_{som} = the net annual amount of N mineralized in mineral soils as a result of loss of soil carbon through a change in land use or management (kg N yr^{-1}) (Equation 1.5)
- $Frac_{leach-[H]}$ = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff (kg N) (from CSRSC (2017) Table 5-1)
- EF_5 = emission factor for N_2O emissions from N leaching and runoff (kg N_2O–N) (from NIR Part 2, Table A6.4-22)

To calculate the annual amount of nitrate runoff (NO_3^-) emissions, Equation 3.1, found below, is used:

$$\textit{Equation 3.1)}\ NO_3^- = [(F_{on} + F_{cr} + F_{som}) \times Frac_{leach-[H]}] \times (62 \div 14)$$

Where

- NO_3^- = annual amount of nitrate emissions by leaching (kg NO_3^-)
    - Note: this value is in units of kg NO_3^- as N yr^{-1}. To convert this unit to kg NO_3^- yr^{-1}, the final solution of Equation 3.1 is multiplied by the molecular mass ratio of NO_3^- to N of (62 ÷ 14 kg NO_3^- kg^{-1} NO_3^--N)
- F_{on} = annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1}) (Equation 1.2)
- F_{cr} = annual amount of N in crop residues (above-ground and below ground), returned to soils (kg N yr^{-1}) (Equation 1.4)
- F_{som} = the net annual amount of N mineralized in mineral soils as a result of loss of soil carbon through change in land use or management (kg N yr^{-1}) (Equation 1.5)
- $Frac_{leach-[H]}$ = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff (kg N) (from CSRC (2017))

3.3.2.4.3 N Emissions Calculations and Uncertainty

Calculations of direct and indirect N_2O emissions from agricultural soils are considerable areas of uncertainty (NIR Report, 2022). In particular, uncertainty arises from using models to estimate GHG emissions because models are considered a simplification of real-life systems (IPCC, 2006). In addition, model inputs introduce uncertainty when activity data and parameters are approximated or averaged, such as manure N, P, and K ratios, emissions factors, and the nitrogen contribution of green manures. Estimations of N_2O emissions are also variable due to the influence of climate, fertilizer application and consumption, and soil type. Consequently, 30-40% uncertainty is associated with modeling N_2O emissions in LCAs of crop production (National Atmospheric Emissions Inventory, ND; National Inventory Report, 2020). The effects of uncertainty were addressed by following IPCC (2019) Tier 2 modelling guidelines, using Canadian-based emissions factor and dry matter partitioning and residue N content, published literature, primary activity data, and expert opinion.

N_2O emissions from crop production on agricultural soils are driven by factors such as the type and amount of N applied and the cropping system to which they are applied (National Inventory Report, 2022). Based on methodology outlined in the NIR report part 2 (2022), N is distributed to specific compounds and fates based on agricultural ecodistricts, which is one level within Canada's National Ecological Framework. There are 1027 ecodistrics in Canada that are characterized by landforms, geology, soil, vegetation, water bodies and fauna (NIR Part 2, 2022). There is a country-specific emission factor (i.e. rates of leakage and loss) for agricultural soils that is calculated for each eco-district that differs based on the source of N, cropping system, topography, soil type, climate, and management practices, such as tillage and irrigation for each ecodistrict (NIR Part 2, 2022). N_2O emissions are calculated by multiplying the amount of N applied to the soil by a unique emission factor based on the ecodistrict in which it was applied. As a result, estimates of N species emissions are different based on the ecodistrict in which it was applied. Uncertainties in emission factors range from 20 to 50% based on IPCC methodology (National Atmospheric Emissions Inventory, ND; NIR Report Part 2, 2022). Uncertainty in this study arises from the fact that emission factors can change from year to year, and are subject to periodic updates when new federal offset protocols are available or versions are updated with new reference materials (Government of Canada, 2022). Furthermore, in this study, emission factors based on agricultural soils, generally (including conventional amendments and operations), are applied to organically managed soils, which may lose or leak N at different rates as a function of the very different character of the nutrient inputs. Last, the spatial unit of the emission factors used (reconciliation unit, ecodistrict) may not reflect the site-specific conditions of each farm in this analysis. However, uncertainty pertaining to emission factors are remedied by using the most recent available data provided by reputable sources (IPCC, NIR, CRSC) and ensuring that values are consistently Canadian-based. Uncertainties and the impact of emission factors on overall impacts are further assessed using sensitivity analysis.

As identified, five emissions factors were used to estimate the amounts of nitrogen from amendments, crop residues, and loss of soil organic matter that end up directly or indirectly entering the atmosphere as N_2O (i.e., EF_1 F_{on}, EF_2 F_{cr}, EF_1 F_{som}, EF_4, and EF_5 applied in Equations 1 and 2 and 3, respectively) and are a source of uncertainty in this analysis. To test the effect that changes to these emissions factors have on estimates of GHG emissions from growing wheat, corn, and soybeans under organic management, a series of sensitivity analyses were performed. Four are based on scaled changes to the EF reflecting the percent uncertainty (20-50% uncertain) given in the National Inventory Report (NIR Part 2, 2022):

- a 50% reduction in the value of the emissions factors applied,
- a 20% reduction in the value of the emissions factors applied,
- a 20% increase in the value of the emissions factors applied, and
- a 50% increase in the value of the emissions factors applied.

Another sensitivity analysis is related to the direct nitrogen emissions factors that result from a meta-analysis conducted by Charles et al. (2017). In this work, the authors propose a global N_2O emissions factor for all organic sources that would replace the current EF_1F_{on} value with a value that is 0.57% (Charles et al., 2017). To test the effect of this alternative, EF_1F_{on} was replaced with the suggested 0.57% value in Equation 1. Changing this EF only affects the direct nitrogen emissions (nitrous oxide) under the CC (long term) impact category. Results of the sensitivity analyses are discussed in Section 3.4.3.2.

3.3.2.4.3.1 Phosphorus Emissions to Water

Developed by the Swiss agricultural research institution Agroscope, the SALCA-P emission models are used to estimate phosphorus emissions to water and are detailed in the Ecoinvent Tool

Model Description (Faist Emmenegger et al., 2018). The following equation, Equation 4, accounts for phosphate leaching to groundwater:

$$\textit{Equation 4)}\ P_{gw} = P_{gwl} \times F_{gw}$$

Where

- P_{gw} = quantity of P leached to ground water (kg P t^{-1})
- P_{gwl} = the average quantity of P leached to ground water for a land use category (kg P ha^{-1})
    - Note: a value of 0.07 kg P ha^{-1} is used in this study for arable land (Prasuhn, 2006)
- F_{gw} = correction factor for fertilization by slurry (dimensionless)
    - Note: a value of $(1+0.2 \div 80 \times P_{sl})$ is used for the correction factor where:
        - P_{sl} = quantity of P contained in the slurry or liquid sewage sludge (kg P ha^{-1})

To calculate the phosphate run-off to surface water, Equation 5 was used:

$$\textit{Equation 5)}\ P_{ro} = P_{rol} \times F_{ro}$$

Where

- P_{ro} = quantity of P lost through run-off to rivers (kg P t^{-1})
- P_{rol} = the average quantity of P lost through run-off for a land use category (kg P ha^{-1})
    - Note: a value of 0.175 kg P ha^{-1} is used in this study for arable land (Prasuhn, 2006)
- F_{ro} = correction factor for fertilization with P (dimensionless)
    - Note: a value of $[(1+0.2 \div 80 \times P_{min}) + (0.7 \div 80 \times P_{sl}) + (0.4 \div 80 \times P_{man})]$ is used for the correction factor where:
        - P_{min} = quantity of P contained in mineral fertilizer (kg P ha^{-1})
        - P_{sl} = quantity of P contained in slurry or liquid sewage sludge (kg P ha^{-1})
        - P_{man} = quantity of P contained in solid manure (kg P ha^{-1})

3.3.2.4.3.2 Changes in Soil Organic Carbon

Soil organic carbon (SOC) is involved in a variety of soil processes and is a crucial aspect of healthy soil carbon stocks (Bessou et al., 2020) alongside soil organic matter (Khan et al., 2021; Lorenz et al., 2017; Zdruli et al., 2017), microbial populations (Khan et al., 2021), and more. The benefits of SOC include increased soil biodiversity (De Beenhouwer et al., 2016; Lal et al., 2015; Miles et al., 2009), species conservation (Flores-Rios et al., 2020), heightened elemental recycling, increased water quality, and food security (Lal et al., 2015) among others. Further, implementing SOC-sequestering land management practices (LMP) could be considered a climate change mitigation solution. These SOC-sequestering practices include no- and reduced-tillage (Apezteguía et al., 2009; Chan, 2008; Mazzoncini et al., 2011; Piccoli et al., 2016; Wang et al., 2011; Wuaden et al., 2020), residue incorporation (Dolan et al., 2006; Han et al., 2018; Lehtinen et al., 2014; Piccoli et al., 2016), and cover cropping (Mazzoncini et al., 2011; Novara et al., 2019; Olson et al., 2014). See Chapter 2 for further discussion of SOC in organic field cropping systems. Despite the importance of SOC, assessing the impact of SOC on agricultural systems in LCA studies is remarkably absent, notably due to a lack of clearly defined procedures (Bessou et al., 2020; Goglio et al., 2015). Thus, including the assessment of SOC in this and other studies is critical.

A literature review conducted as part of a nation-wide characterization of organic field cropping systems, explored the current approaches to modelling SOC flux in mid-latitude, agricultural, field crop life cycle assessment studies published between 2010 and 2022. With no clear procedure to address SOC in LCA studies, the literature review explored current approaches used by different scholars to characterize change in SOC and details how LMPs are modelled with each approach. The review identified various approaches to estimating changes in soil C, including downloadable software packages, simple C models, and field sampling, some approaches even being applicable for modelling SOC in organic systems. Studies show, when tested, the IPCC Tier 2 model was able to closely estimate experimental data of SOC change, outperforming other popular models such as ICBM and RothC (Thiagarajan et al., 2022). Fortunately, the IPCC Tier 2 model is also embedded in a Canadian-specific whole-farm GHG emissions accounting tool: Holos. Holos was developed by Agriculture and Agri-Food Canada and is used to model and test on-farm emissions reduction methods (Agriculture and Agri-food Canada, 2022c; NDC Partnership, n.d). Both farmers and researchers use the model to simulate whole-farm scenarios, including a variety of management practices such as tillage practice, crop rotation, nutrient amendments, and changes to livestock feed, among many others (Agriculture and Agri-food Canada, 2022a; NDC Partnership, n.d.). Although other downloadable software packages and SOC estimation techniques were identified through the literature review that may have been appropriate for use with this study, the Canadian specificity of Holos and the performance of the IPCC Tier 2 model made Holos the overall best choice to model soil organic carbon changes and the impact of LMPs on changes in SOC stocks. The model's ability to incorporate aspects of climate, geography, management practices, and amendments in addition to its Canadian soil and climate specificity made it the ideal choice for modelling SOC flux in this analysis.

The calculations embedded in Holos to estimate SOC change are from IPCC Chapter 3 (IPCC, 2000; Pouge et al., 2022). Required inputs to Holos for determining the change in soil organic carbon (ΔC) include:

- Farm location expressed as polygons (data from farm inventory);
- Crop field and/or rotations (data from farm inventory);
- Crop yields;
- Field areas;
- Nutrient application or mineral amendments (data from farm inventory);
- Green Manures or intercrops (data from farm inventory); and
- Tillage practices.

Holos polygons are chosen based on farm coordinates and account for regional soil classification differences and historical weather (Figure 3-8). The Holos user can also define the time period over which the model initiates itself and the number of years over which the historical field and/or rotation is assumed to have remained stable. A 15-year run-in period was set as the default in Holos between the IPCC Tier 2 suggested run-in periods of 5 and 20 years (Pouge et al., 2022).

The output of Holos is on a whole-farm basis, with the SOC changes represented as a positive (indicating SOC gains) or negative (indicating SOC losses) value of kg C ha^{-1}. These results were exported to Excel and the column of the change in soil carbon values (kg C ha^{-1}) were averaged over years under organic management, which yielded a ΔC value for a single crop in the modeled rotation in a single year (kg C ha^{-1} yr^{-1}). This value was then normalized to the functional unit using the yield associated with each crop on the farm, and multiplied by the molecular weight ratio of CO_2 to C ($44 \div 12$) to obtain SOC in units of kg CO_2 t^{-1} for each crop. If the SOC change for a crop was negative, it was used subsequently to calculate one source of N emissions to the atmosphere that results from the loss of soil organic matter.

Figure 3-8 Holos polygons were compiled into a nation-level polygon map. Holos polygons detail information about SLC polygon; ecozone; eco-district; soil type (i.e., soil great group, texture, the proportion of clay, sand, and loam in the soil, and drainage class); hardness zone (i.e., hardness zone and proportion of hardness zone); and NASA climate data (Agriculture and Agri-food Canada, 2022a; NASA, 2022)

While Holos is a Canadian-based software that draws from methods outlined in the IPCC Tier 2 model that employs country-specific static parameters and includes some default SOC stock values, calculations of SOC are influenced by several factors (Niero et al., 2015; Joensuu et al., 2021). Such factors include soil type, management practice (tillage vs no tillage), organic amendments (ex. manure, mineral fertilizers), residue management, green manure planting, and climatic conditions such as temperature and precipitation (Niero et al., 2015). Furthermore, while a small fraction of previous organic LCA studies have included soil organic carbon changes as part of their quantification of net life cycle GHG emissions, current LCA methodologies are not sufficiently developed to confidently include SOC in an assessment, and so studies have opted for its exclusion (Knudsen et al., 2019). Consequently, there is a 44% uncertainty associated with modeling SOC changes and CO2 emissions (National Inventory Report, 2020). As a result of limited credibility in SOC accounting and robust modeling, there is great uncertainty associated with SOC changes. However, this is remedied by using a Canadian-based whole-farm modeling software, IPCC (2019)

Tier 2 methodology, and consultation with the literature, experts and representatives at Agriculture and Agri-Food Canada.

Changes in levels of soil organic carbon can have a substantial effect on estimates of net GHG emissions from crop production (Viana et al., 2022), particularly as soils can be either a source or sink of atmospheric carbon depending on their composition, climatic conditions, current management practices, and history of utilization. However, one factor that can affect soil carbon modelling outputs for which there is little direct data to draw on is how the model initially estimates starting soil carbon levels. The spin-up period is the length of time the model assumes the farm is operating under current conditions, which affects the initial carbon value, the rate of SOC accumulation and when SOC change approaches steady-state. In the Holos model a model run-in period is used to characterize the starting soil carbon level. During the original modelling of Holos, a default run-in period of 15-years was set as a mid-range value between the IPCC Tier 2 suggested values of 5 and 20 years (Pouge et al., 2022). To test the model's sensitivity on the run-in period, and subsequently how life cycle GHG emission results and SOC change were affected, a sensitivity analysis was performed on the run-in period. Specifically, the Holos models for each farm in this analysis were re-run using a 5-year run-in period and then a 20-year run-in period. Results of the sensitivity analysis are discussed in Section 3.4.3.1.

3.3.3 Limitations

3.3.3.1 Sample Size

This study has some limitations. First, considering the quantitative nature of this analysis, results and interpretations are limited by a small sample size. This study is one of two parts of a Canada-wide characterization of the life cycle environmental performance of organic field crop production. Primary data collection that occurred from May to November 2021 yielded 50 completed surveys from organic field crop farmers from Ontario, Quebec, Manitoba, Saskatchewan, Alberta, and British Columbia. In this analysis, data was received from a total of 18 farms, 6 located in Quebec and 12 in Ontario. These farms provided a total of 33 farm-crop LCI datasets for organic wheat, corn, and soybeans across both provinces. A more representative sample size was hindered by 1) COVID-19 that restricted travel and in-person data collection, 2) no formal database of organic field crop farmers, 3) the length of the survey and the time required of farmers to provide detailed LCI data.

However, a great deal of effort was invested in regularly following up with farmers, scheduling phone calls to complete the survey with a researcher, utilizing agro-experts and ‘champions’ to disseminate the survey, and advertising the survey through provincial and national agricultural organizations. An additional paper for publication was written as part of this national project and detail survey recruitment and retention in agricultural LCAs with suggestions for future studies.

Additionally, a repercussion of the smaller sample size in this analysis is the inability to report results based on individual management practices. While results could be aggregated and reported based on geography and yield, this could not be done for individual management practices. And so, results in regards to management practices, such as manure application, green manure incorporation, cover cropping, and mineral amendments were reported generally. However, a majority of farms utilized some form of an organic management practice and efforts were taken to ensure they were modelled accurately by clarifying units, sources, rates of application, and timing applied with individual farmers and supplemented the data, where necessary, using Canadian information.

3.3.3.2 Lack of Soil Organic Carbon Change Research in LCA studies

As discussed previously, there is limited research and inclusion of soil organic carbon changes in organic field crop LCAs. As a result, results and interpretations in this analysis are limited by similar discussions and methodology in the literature. However, several organic field crop LCAs were identified, with and without SOC, and used to corroborate results. Furthermore, soil carbon experts at Agriculture and Agri-Food Canada who developed Holos were consulted regularly to ensure modelling was accurate and results were being interpreted correctly.

3.4 Results

The results are presented as follows: overview of farms modeled; average environmental impacts for Eastern Canada; average environmental impacts by province; average environmental impacts by yield; and sensitivity analysis.

3.4.1 Overview of Farms Modeled

Table 3-7 presents a summary of the organic wheat, corn, and soybean data regarding data collected from Ontario and Quebec. Across Eastern Canada, data was received from a total of 18 farms, in which 6 were from Quebec and 12 were from Ontario. These farms provided 33 farm-crop LCI datasets for organic wheat, corn, and soybeans across both provinces. In Ontario, the number of LCI datasets for organic wheat, corn, and soybeans totaled 5, 6, and 9, respectively. And in Quebec, the number of LCI datasets for organic wheat, corn, and soybeans totaled 4, 4, and 5, respectively. Due to the lack of data concerning provincial average yields for organic production, conventional yield ranges for wheat, corn, and soybeans are presented in Table 3-7. As a result, average yields from the producer data from this study are within range or close to provincial average yields for conventional wheat, corn, and soybean from 2018 to 2021.

Based on data provided by the Ontario farmers, the average seeded area of organic wheat was 46.8 ha with a total area of 234.0 ha. The average nitrogen applied includes N from animal manure, compost, green manures, and cover crops, which was 44.5 kg N t^{-1} for organic wheat in Ontario. The average wheat yield was 4.8 t ha^{-1}, which falls just below the provincial average wheat yield of 5.2 to 6.1 t ha^{-1} in Ontario (OMAFRA Field Crop Team, 2022; Statistics Canada, 2021b). Next, the average seeded area for organic corn was 49.2 ha with a total area of 295.3 ha. The average nitrogen applied to organic corn in Ontario was 18.4 kg N t^{-1}. The average organic corn yield in Ontario was 10.3 t ha^{-1}, which is within the range of the provincial average yield for corn grain (Table 3-7) (Statistics Canada, 2022a; Statistics Canada, 2022b). Last, the average seeded area of organic soybean in Ontario was 36.4 ha, with a total area of 327.9 ha. The nitrogen applied to organic soybeans averaged 16.5 kg N t^{-1}. The average organic soybean yield provided by Ontario farmers was 2.6 t ha^{-1}, which is within the range of 2.2 to 3.5 based on the provincial average yield (Statistics Canada, 2022a; Munroe, 2022).

Based on data provided by Quebec farmers, the average seeded area for organic wheat was 54.5 ha, with a total area of 218 ha. The average nitrogen applied to organic wheat was 202.0 kg N t^{-1}. And, the average organic wheat yield was 2.2 t ha^{-1}, which was just below the provincial average wheat yield of 2.3 to 3.6 t ha^{-1} (Statistics Canada, 2022c). Next, the average seeded area for the organic corn was 52.3 ha, with a total of 209.1 ha. Furthermore, the average nitrogen applied was 9.4 kg N t^{-1}. The average organic corn yield was 9.8 t ha^{-1}, which is a little below the provincial average from 2018 to 2021 (Table 3-7) (Statistics Canada, 2022b). Last, the average seeded area was 63.6 ha, with a total area of 316.7 ha. Moreover, the average nitrogen applied to organic soybean production in Quebec was 23.3 kg N t^{-1}. And the average organic soybean yield was 3.6 t ha^{-1}, which is a little higher than the provincial average range of 2.9 to 2.5 t ha^{-1} (Statistics Canada, 2021a; Statistics Canada, 2022b).

For all of Eastern Canada, the average seeded area of organic wheat was 50.2 ha, with a total area of 452.0 ha. The average nitrogen applied to organic wheat was 114.5 kg N t^{-1}. And the average organic wheat yield was 3.7 t ha^{-1}. Next, the average seeded area for organic corn was 50.4 ha, with a total area of 504.4 ha. The average nitrogen applied to organic corn was 14.8 kg N t^{-1}. And the average organic corn yield was 10.1 t ha^{-1}. Last, the average seeded area of organic soybean was 46.0 ha, with a total area of 644.7 ha. The average nitrogen applied to organic soybeans was 18.9 kg N t^{-1}. And the average yield was 3.0 t ha^{-1}.

Table 3-7 Summary of farms modelled in Ontario and Quebec, and all of Eastern Canada

Province	Attribute	Wheat	Corn	Soybean
Ontario	# of LCI datasets (provided by producers to this study)	5	6	9
	Avg. Farm Area (ha)	46.8	49.2	36.4
	Avg. Nitrogen Applied (kg N t^{-1})	44.5	18.4	16.5
	Avg. Yield (based on producer data from this study) (t ha^{-1})	4.8	10.3	2.6
	Provincial Avg. Yield (t ha^{-1})	5.2-6.1[2,6]	9.5[1,5]-11.8[1]	2.2[3]-3.5[1]
Quebec	# of LCI datasets (provided by producers to this study)	4	4	5
	Average Farm Area (ha)	54.5	52.3	63.3
	Avg. Nitrogen Applied (kg N t^{-1})	202.0	9.4	23.3
	Avg. Yield (based on producer data from this study) (t ha^{-1})	2.2	9.8	3.6
	Provincial Avg. Yield (t ha^{-1})	2.3-3.6[6]	8.9[6]-9.6[5]	2.9[4,5]-3.5[5]
Eastern Canada	# of LCI datasets (provided by producers to this study)	9	10	14
	Avg. Farm Area (ha)	50.2	50.4	46.0
	Avg. Nitrogen Applied (kg N t^{-1})	114.5	14.8	18.9
	Avg. Yield (based on producer data from this study) (t ha^{-1})	3.7	10.1	3.0

[1] Statistics Canada (2022a)
[2] OMAFRA (2022)
[3] Munroe, J. (2022)
[4] Statistics Canada (2021)
[5] Statistics Canada (2022b)
[6] Government of Ontario (2021)
[7] Institut de la statistique Quebec (2022)

3.4.2 Climate Impacts of Organic Field Crop Production in Eastern Canada

The total cradle-to-harvest gate life cycle impact assessment results are reported for the six main impact categories under analysis in this study: climate change (long term), fossil and nuclear energy demand, freshwater acidification, freshwater eutrophication, land occupation and biodiversity, and water scarcity. Impacts are associated with the production of 1 tonne of harvested organic wheat, corn, and soybean in Eastern Canada (Ontario and Quebec). This section also presents a contribution analysis, which represents the activities or processes that contribute the most to the total impacts. Appendix O includes the total cradle-to-harvest gate life cycle impact assessment results for the remaining impact categories excluded from this analysis (freshwater ecotoxicity, human toxicity (cancer), human toxicity (non-cancer), ionizing radiation, mineral resource use, ozone layer depletion, particulate matter formation, photochemical oxidant formation, and terrestrial acidification).

Results are reported as weighted averages based on production tonnage output. Importantly, results associated with CCLT (e.g. Figure 3-9) are reported on the basis of a number of major sub-system activities: “SOC Change”, “Nutrient Application”, “Field Operations”, and “Seed”. “Nutrient Application” is the sum of the field-level nitrogen dioxide emissions, and emissions associated with manure application, organic amendments applied, green manures, and cover crops. “Field Operations” are the sum of all farm machinery-related emissions associated with production. “SOC Change” represents the net change in the soil carbon, reported as CO_2 in the total CCLT impact results (unless stated otherwise). A negative SOC value demonstrates sequestered carbon while a positive SOC value is a loss of CO_2 emissions to the atmosphere. Last, “Seed” represents emissions associated with seed provisioning.

Table 3-8 is the cradle-to-harvest gate impact assessment results for climate change (long term), fossil and nuclear energy deprived, freshwater acidification and eutrophication, land occupation and biodiversity, and water scarcity impacts associated with the production of 1 tonne of crop harvested of organic wheat, corn, and soybean in Eastern Canada (Ontario and Quebec). In general, the highest impacts across most impact categories were for wheat, which had the highest nitrogen inputs and medium yields relative to soy and corn. The lowest impacts were for soy, which had the lowest yields and low nitrogen inputs. The only exception was for land use, which was the highest for corn.

Table 3-8 Cradle-to-harvest gate impact assessment data for CCLT (including average soil organic carbon change), fossil and nuclear energy deprived, freshwater acidification and eutrophication, land occupation and biodiversity, and water scarcity impacts associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean in Eastern Canada (Ontario and Quebec)

	Wheat	**Corn**	**Soybean**
Climate Change (long term) (kg CO_2eq)	520	200	110
Soil Organic Carbon Change (kg CO_2)	-470	-160	-230
Fossil and Nuclear Energy Deprived (MJ Deprived)	2900	1800	1600
Freshwater Acidification (kg SO_2 eq)	3.3E-10	1.1E-10	9.7E-11
Freshwater Eutrophication (kg $PO4^-$ lim. eq)	0.012	0.0050	0.0071
Land Occupation and Biodiversity (m^2 arable land eq.yr)	4.0	4.2	2.3
Water Scarcity (m^3 world-eq)	230	140	90

CCLT impact results, including average soil organic carbon change, for wheat, corn, and soybean are 520, 200, and 110 kg CO_2 eq per tonne crop harvested, respectively (Table 3-8). The wheat value in this analysis was similar to the total GWP (including soil carbon change) found by Rebolledo-Levia et al. (2022) and Knudsen et al. (2014) where they found wheat totaled 492 and 527 kg CO_2 eq per tonne crop, respectively. However, when soil carbon change is not included, the CCLT impact results for wheat total 990 kg CO_2 eq per tonne crop harvested, being quite a bit higher than studies such as Pelletier et al. (2008), Moudry et al. (2018), and Williams et al. 2010 where wheat excluding soil carbon totaled 382, 423, and 786 kg CO_2 eq per tonne crop, respectively. In this this, corn and soybean CCLT impact results (not including soil carbon change) total 360 and 330 kg

CO_2 eq per tonne crop harvested, respectively. The corn and soybean values were greater than the GWP found by Pelletier et al. (2008) where corn and soybeans totaled 256 and 190 kg CO_2 eq per tonne crop, respectively. Importantly, the limited inclusion of SOC change in total GWP results in the literature inhibits a direct comparison of CCLT impact results including SOC change.

In this study, “Nutrient Application” was the biggest contribution to CCLT impacts (Figure 3-9). “Nutrient Application” accounted for 87.9%, 85.2%, and 74.7% of total impacts for wheat, corn, and soybean production impacts, respectively. It is also evident that high nitrogen application in the wheat system was responsible for the much higher impacts for this system, arising from direct and indirect N_2O emissions, which represent 77.2%, 65.4%, and 64.9% of the “Nutrient Application” activity for organic wheat, corn, and soybean production, respectively (Appendix R). Both Pelletier et al. (2008) and Rebolledo-Levia et al. (2022) identified field-level emissions as ‘hotspots’ or drivers of wheat production-related climate impacts. Similarly, Moudry et al. (2018) assessed the GWP (not including SOC) of organic wheat, rye, and oats and found organic wheat to have the highest impact (423 CO_2 eq per tonne crop), followed by oats (303 CO_2 eq per tonne crop) and rye (298 CO_2 eq per tonne crop). Therefore, despite having the highest yield (3.5 t ha^{-1}) relative to oat (2.6 t ha^{-1}) and rye (2.9 t ha^{-1}), field emissions and field operations were the highest for organic wheat (Moudry et al., 2018). “Field operations” were the next biggest contributor to overall climate change impacts, at 8.9%, 14.1%, and 20.6% of the total, for wheat, corn, and soybeans, respectively (Figure 3-9). “Seed Provision”, representing activities associated with producing seeds upstream, contributed only 3.2%, 0.7%, and 4.7% of the total impacts for wheat, corn, and soybean production, respectively. Importantly, there was net SOC sequestration (negative value), which reduced the overall CCLT impacts for all three crops (Figure 3-9). The wheat production resulted in the largest SOC sequestration rates at -470 kg CO_2 per t crop harvested with corn and soybeans sequestering -160 and -230 kg CO_2 per t crop harvested, respectively.

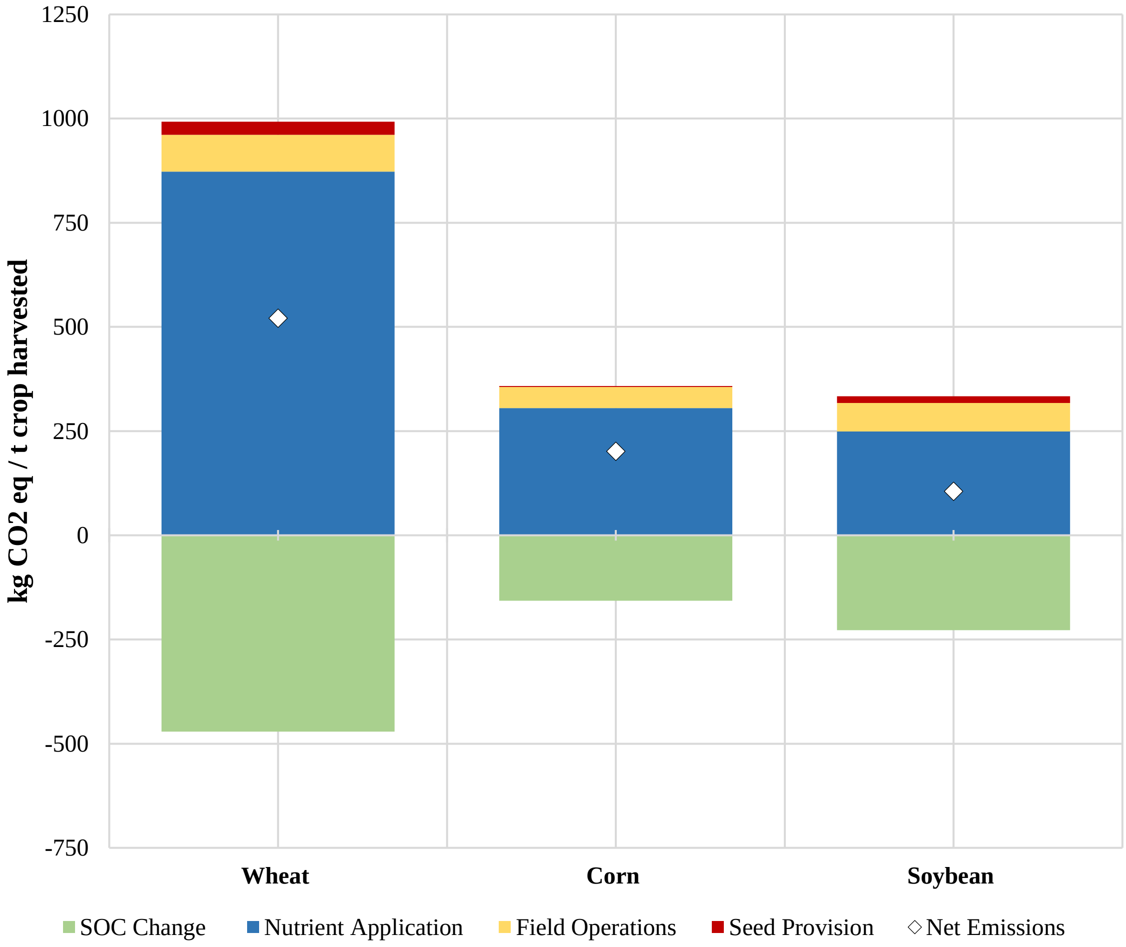


Figure 3-9 Cradle-to-harvest gate CCLT emissions associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean in Eastern Canada. "Nutrient Application" refers to field-level nitrous oxide emissions associated, and emissions associated with manure acquisition, mineral amendments, as well as green manure, cover crop growth, and impacts from leguminous crop. "SOC Change" refers to CO_2 emissions from crop production. "Field Operations" refers to all farm machinery from crop production. "Seed Provision" refers to activities associated with producing seeds upstream.

Fossil and nuclear energy resource depletion results are 2900, 1800, and 1600 MJ deprived per tonne crop harvested, for wheat, corn, and soybean production, respectively (Table 3-8). The value for wheat is higher than the energy use found by Tuomisto et al. (2012) where organic wheat was 1705 MJ per tonne. However, the soybean value in this study was lower than the energy use identified by Kamali et al. (2017) where organic soybeans were 2149 MJ per tonne. "Nutrient Application" accounted for 50.5%, 59.5%, and 31.6% of total impacts for organic wheat, corn, and soybean production, respectively (Appendix S). Similarly, “Field Operations” accounted for 41.9%, 39.4%, and 61.6% of the total impacts associated with organic wheat, corn, and soybean production, respectively. It is also evident that high “Nitrogen Application” impacts were driven by growing green manure crops and manure application in wheat production system (Appendix S). Knudsen et al. (2014) conducted a similar analysis, whereby the environmental impacts of a prior green manure in rotation were allocated to the impacts of the cash crop. They found that contributions from a green manure crop were a considerable aspect of impacts associated with the main crop. Similarly, growing cover crops, mineral amendment extraction, and again, manure application were drivers of “Nutrient Application” impacts for the corn production system. Last, to a lesser extent, “Nutrient Application” for soybean production was also driven by growing green manures and acquiring manure. Pelletier et al. (2008) and Verdi et al. (2022) also found that energy use was primarily driven by fuel inputs and fertilizer production, machinery practices and lower yields.

Freshwater acidification impacts are 3.3E-10, 1.1E-10, and 9.7E-11 kg SO_2 eq per tonne crop harvested for wheat, corn, and soybean production, respectively (Table 3-8). Wheat, corn, and soybean results in this analysis were much lower than those found in the literature likely due to differences in LCIA methodology. However, Pelletier et al. (2008) found similar trends where acidifying emissions were highest for wheat (9.7 kg SO_2 eq per tonne crop), followed by corn (5.7 kg SO_2 eq per tonne crop), and soybeans (5.4 kg SO_2 eq per tonne crop). “Nutrient Application” was the biggest contributor to overall freshwater acidifying emissions for all three organic field crops constituting 96.4 to 97.8% of the total emissions (Appendix T). These impacts are a result of potential N losses via leaching and volatilization from applied animal manures, compost, green manure incorporation, and cover cropping, below-and aboveground residue decomposition, and the nitrogen mineralized from SOM loss due to cropland management. These results are similar to that of Verdi et al. (2022) in which 60% of acidification was from field-level emissions, and Pelletier et al. (2008) that reported 88% of acidifying emissions was from field-level emissions where 78% was associated with green manure nitrogen production.

Freshwater eutrophication impacts are 0.012, 0.0050, and 0.0071 kg $PO4^-$ lim. eq per tonne crop harvested for wheat, corn, and soybean production, respectively (Table 3-8). Wheat, corn, and soybean results from the literature are larger than those found in this analysis, likely due to differences in LCIA methodology, as well as agro-climatic conditions, and site-specific management practices. Fedele et al. (2014) found for soybeans that eutrophication impacts totaled 0.34 kg PO_4^{-3}

eq per tonne crop, and Verdi et al. (2022) reported 1.6 kg PO_4^{-3} eq per tonne crop for wheat. Similar to freshwater acidification, “Nutrient Application” was the dominant source of these impacts (73.7%, 90.3%, and 75.6% of the total for organic wheat, corn, and soybean production, respectively) (Appendix U), largely due to the potential phosphate emissions from erosion, which contributed 46%, 34.5%, and 56.9% of the impacts in “Nutrient Application” for organic wheat, corn, and soybean production, respectively. Similarly, Verdi et al. (2022) and Boone et al. (2016) found that eutrophication impacts are driven by fertilizer use releasing P emissions via erosion and leaching, nitrates via leaching, ammonia from over-fertilization, and nitrous oxides emissions from field operations. Furthermore, “Seed Provisioning” was a notable contribution to the total impact for organic wheat (20.4%) and soybeans (16.6%), as well as manure NPK acquisition (from the synthetic fertilizer) contributing approximately 14-16% to “Nutrient Application” impacts for all three crops.

Land occupation (biodiversity) total impacts associated with organic wheat, corn, and soybeans are 4.0, 4.2, and 2.3 m^2 arable land eq. yr per t crop harvested, respectively (Table 3-8). “Nutrient Application” was a dominant source of the total impacts, contributing 61.0%, 79.6%, and 46.2% from organic wheat, corn, and soybean production, respectively. Manure acquisition constituted 41.6%, 21.8%, and 37.1% of impact results for organic wheat, corn, and soybean production, respectively. Interestingly, the greatest proportion of impacts for organic corn is mineral amendments (44.8%). Similarly, but to a lesser extent, cover cropping represented 10.9% of the total impacts associated with organic corn production. While impacts from green manure growth are variable across all three organic field crops, it was a significant contribution to land occupation from organic wheat production (17.5%). “Field Operations” (the sum impact of combine harvesting, sowing, fertilizing, rotary harrowing, rolling, offset disc harrowing, ploughing, cultivating chiseling, spring tine harrowing, hoeing, and currying (by weeder)) constituted 31.9%, 19.6%, and 46.4% of total land occupation (indirect) from organic wheat, corn, and soybean production. Figure 3-10 illustrates the contributions to land occupation (biodiversity) from individual parameters. See Appendix V for all impact results related to land occupation (biodiversity).

The results for organic wheat can be attributed to the following reasons: 1) lower yields, thus requiring more land to produce 1 tonne of crop (Ridoutt & Garcia, 2020), 2) the land required to grow green manures, 3) the land required to acquire seed, and 4) indirect land occupation from upstream processes related to seed provisioning, green manure growth, mineral amendment acquisition, field operations and manure acquisition. Despite higher average yields, the results for organic corn can be attributed to the land required to grow cover crops and the indirect impacts associated with upstream processes of the mineral amendments applied. Soybeans had the smallest impact due to less nutrients applied, which are associated with less required land. Importantly, wheat, corn, and soybean results in this analysis are not directly comparable to similar studies due to differences in LCIA methodology. Results based on IMPACTWorld+ are limited by the absence of a direct ‘land use’ impct category. While “Land Occupation, Biodiversity” is considered a proxy for land use impacts on ecosystem services (Bulle et al., 2019), results in this analysis are much smaller than other similar studies and thus, difficult to compare. For example, Williams et al. (2010) reported a land occupation total of 4100 m^2 per tonne of wheat produced. For soybean production, Fedele et al. (2014) reported 2627 m^2a per tonne crop and Kamali et al. (2017) reported 2377 m^2 year eq per tonne. Overall, studies demonstrated that land use impacts are most often driven by yield and crop productivity, which was found in this study alongside impacts from indirect and upstream land use.

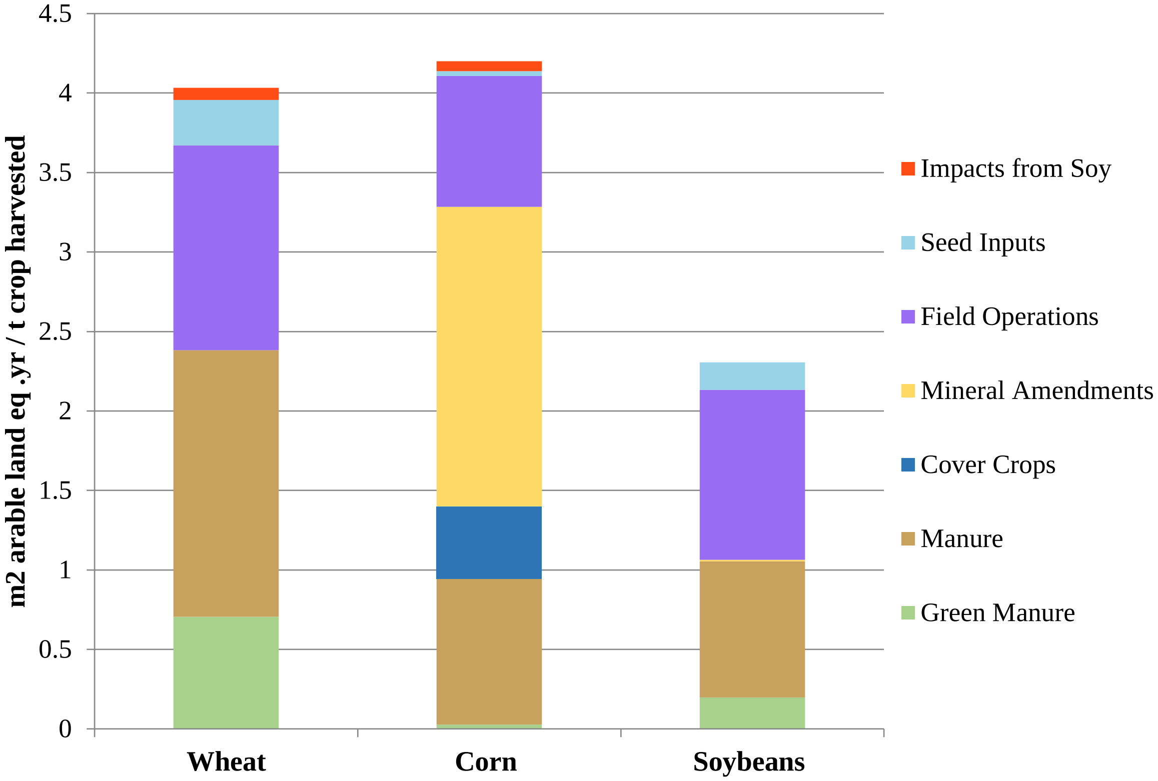


Figure 3-10 Cradle-to-harvest gate land occupation, biodiversity (m^2 arable land eq. yr) associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean in Eastern Canada. 'Field Operations' include combine harvesting, sowing, fertilizing, rotary harrowing, rolling, offset disc harrowing, ploughing, cultivating chiseling, spring tine harrowing, hoeing, and currying (by weeder).

Water scarcity impact results for organic wheat, corn, and soybeans are 230, 140, and 90 m^3 world-eq. per t crop harvested, respectively (Table 3-8). Unlike water use or water consumption, organic field crop literature did not discuss water scarcity. The main sources of impacts to water scarcity in this study varied among the crops. "Nutrient Application" and "Seed Inputs" were the dominant sources to water scarcity from wheat and soybean production (Figure 3-11). "Nutrient Application" accounted for 36.1% and 31.4% and "Seed Inputs" accounted for 58.0% and 56.2% of wheat and soybean production impacts, respectively. In contrast, "Nutrient Application" accounted for 92.9% of the total impacts from organic corn with large contributions from "Cover Crops" (12.8%) and "Mineral Amendments" (56.7%). "Manure" acquisition accounted for 26.5%, 20.7%, and 28.7% of "Nutrient Application" impacts for wheat, corn, and soybean production, respectively. See Appendix W for all impact results related to water scarcity.

Similar to 'Land Occupation, Biodiversity', results for water scarcity based on IMPACTWorld+ impact assessment methodology are limited by the absence of a direct 'water use' or 'water consumption' impact category. As a result, traditional impacts, such as the quantity of water consumed by organic field crop production cannot be reported, rather, water scarcity quantifies the potential of water deprivation to either humans or ecosystems based on the impacts of water consumption in a given area using the AWARE method (Boulay et al., 2018). As a result, water consumption related to wheat caused the greatest impacts to water scarcity, followed by corn and soybeans.

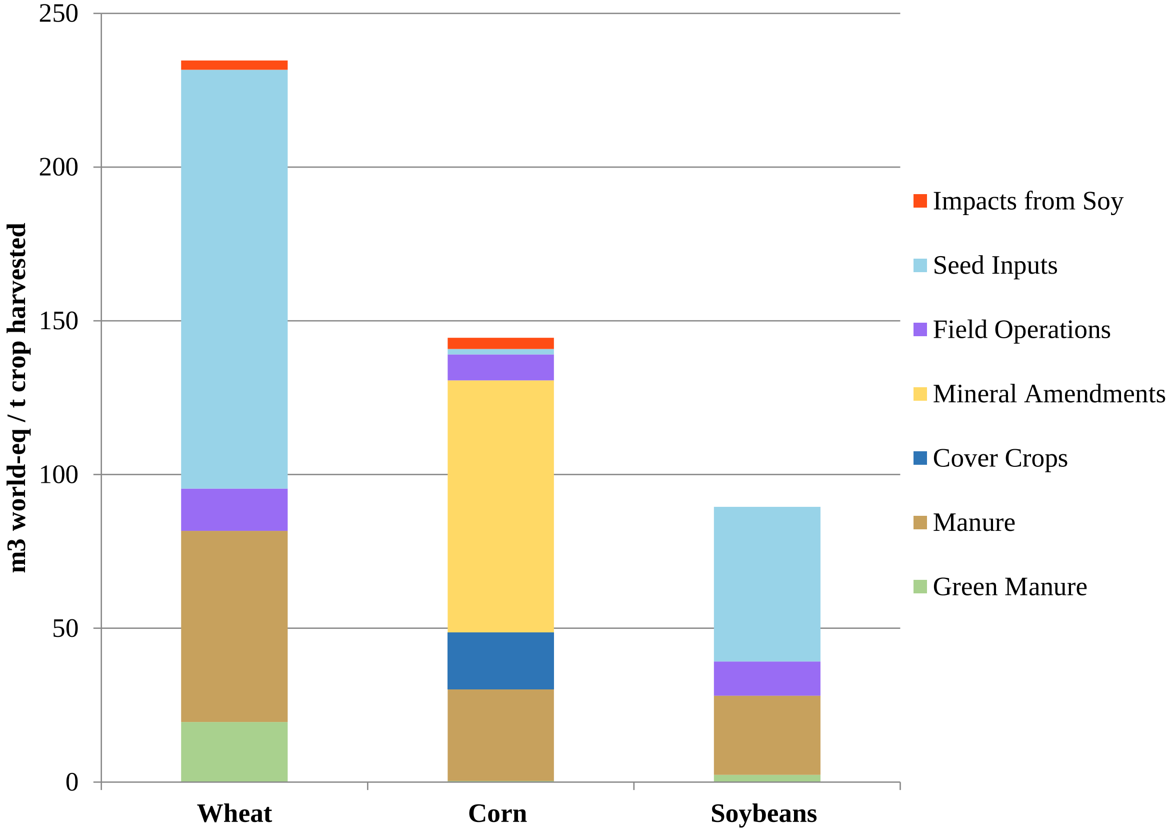


Figure 3-11 Cradle-to-harvest gate water scarcity impacts (m^3 world-eq) associated with the production of 1 t of crop harvested for organic wheat, corn, and soybean in Eastern Canada. "Field Operations" include combine harvesting, sowing, fertilizing, rotary harrowing, rolling, offset disc harrowing, ploughing, cultivating chiseling, spring tine harrowing, hoeing, and currying (by weeder).

3.4.3 Climate Change Impacts by Province

To understand whether impacts were different by province, the cradle-to-harvest gate CCLT emissions associated with the production of 1 t crop harvested of organic wheat, corn, and soybean were averaged based on production weighted output for Ontario and Quebec, separately (Table 3-9). See Appendix Y for all contributing parameters to CCLT impacts by province. Two weighted averages based on the mass of harvest were calculated for Quebec organic wheat, one with all the data, and one that excluded an outlier, that had a very low yield (0.6 t ha^{-1}), but also had a low seeded area (35 ha), therefore it affected the weighted average.

CCLT results for wheat were considerably different for the two provinces, at 160 and 1200 kg CO_2 eq per tonne crop harvested for Ontario and Quebec, respectively. The average yield of organic wheat in Quebec was also less than half of the average yield in Ontario. Furthermore, the impacts from the main contributing activities or processes (i.e. negative SOC change, nutrient application, field operations, and seed provisioning) were higher for wheat in Quebec than in Ontario. Nutrient application was a major contributor (92% of total CCLT) for wheat in Quebec (Figure 3-12). This is driven by much higher nutrient application rates, particularly of manure, in Quebec than Ontario. Additionally, Quebec organic wheat production was associated with a greater amount of SOC sequestration, likely as a result of the larger carbon input supplied from high manure application rates (Figure 3-12). Nevertheless, the SOC sequestration did not reduce the nutrient application emissions sufficiently to lower the overall climate change impacts.

For corn, results were more similar, at 250 and 130 kg CO_2 eq per tonne crop harvested for Ontario and Quebec, respectively. Corn yields were also more similar in Ontario (10.3 t ha) and Quebec (9.8 t ha), but the relationship between yield and impacts was opposite to that seen in wheat. This is likely due to higher SOC sequestration rates in Quebec. Notably, the types of N inputs were similar for wheat, corn, and soy in Quebec. For wheat and soybeans, the predominant inputs were green manure N and manure, while manure was the predominant input for corn in Quebec. In addition, there was a higher manure inputs in Quebec than Ontario, which is a source of both carbon and nitrogen, therefore contributing to greater increases in soil C. But overall, the higher SOC rates in Quebec offset the higher N emissions.

CCLT impact results for soybeans were higher in Ontario than Quebec (Figure 3-12). Impacts from nutrient application were a little higher in Ontario (76%) than Quebec (73%), again, likely leading to greater SOC sequestration per t crop harvested.

Table 3-9 Cradle-to-harvest gate CCLT emissions associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean averaged for Ontario and Quebec. Key contributing parameters include "Impact of SOC Change" (CO_2 emissions), "Nutrient Application" (field-level nitrous oxide emissions, animal manure application, organic amendments, green manures, cover crops, and impacts from leguminous crop), "Field Operations" (farm machinery using during production), and "Seed" (seed provision). "Total (Excluding SOC)" excludes contributions from SOC flux. "% Contribution NA:Total" is the percent contribution of nutrient application-related emissions to the total (minus SOC).

Climate Change (long term) Impacts –
Totals and by Farm Activity Contributions
(kg CO_2 eq / t crop harvested)

Wheat	**Average Yield ($t\ ha^{-1}$)**	**Climate Impact of SOC Change**	**Nutrient Application**	**Field Operations**	**Seed**	**Total**	**Total (Excluding SOC)**	**% Contribution to Emissions NA:Total (Excluding SOC)**
ON Average	4.8	-370	420	82	25	160	530	80%
QC Average	2.2	-660	1700	100	45	1200	1800	92%
*****QC Average	2.7	-590	1500	92	40	1100	1700	92%
Corn								
ON Average	10.3	-110	290	60	2.2	250	350	82%
QC Average	9.8	-230	330	37	3.0	130	370	90%
Soybean								
ON Average	2.6	-270	340	90	19	180	450	76%
QC Average	3.6	-190	180	53	13	51	240	73%

*Quebec average results for wheat with outlier (lowest yield) removed

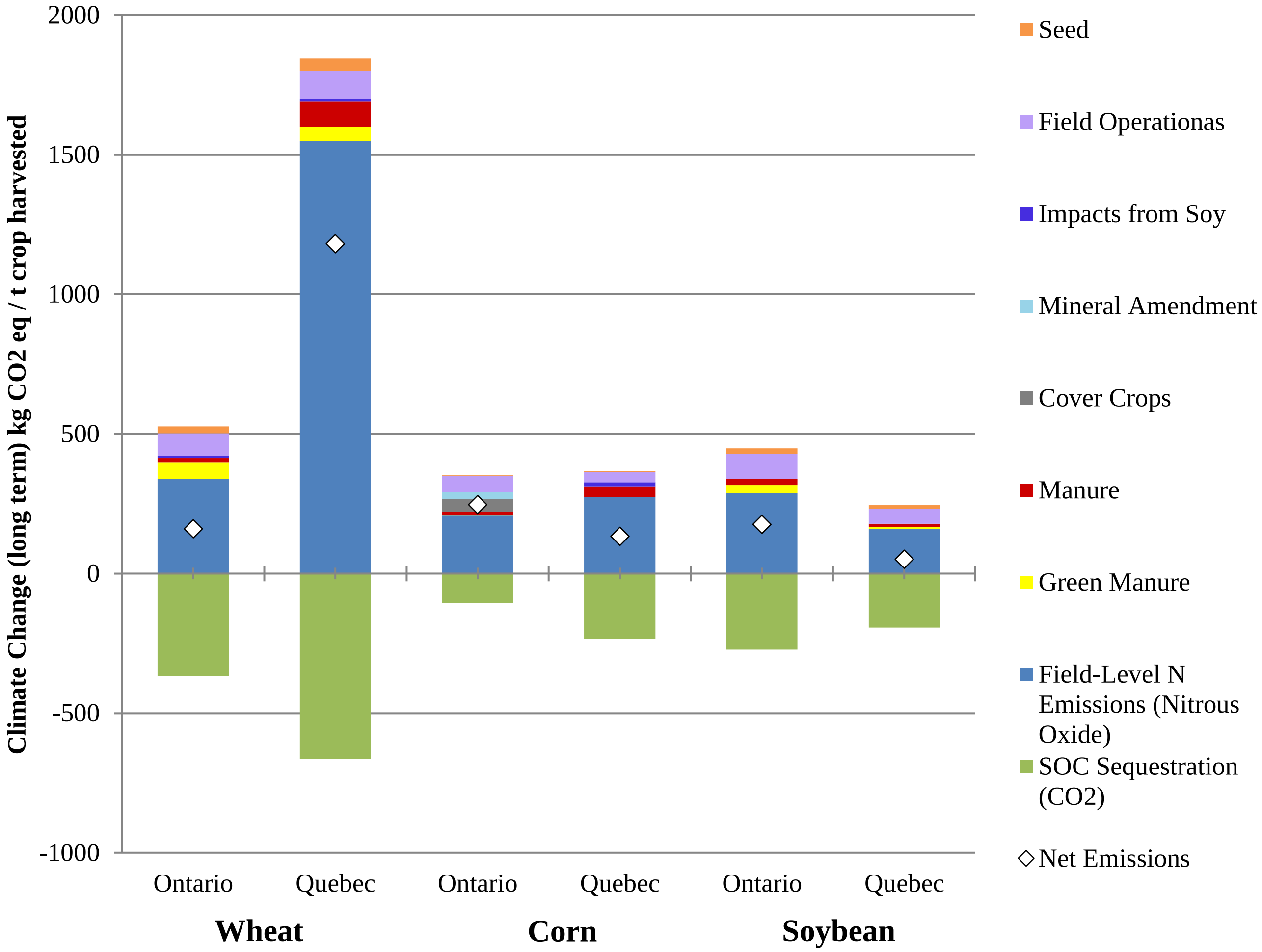


Figure 3-12 Cradle-to-harvest gate CCLT emissions associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean in Ontario and Quebec. "Field Operations" include combine harvesting, sowing, fertilizing, rotary harrowing, rolling, offset disc harrowing, ploughing, cultivating chiseling, spring tine harrowing, hoeing, and currying (by weeder). "Field-Level N Emissions (Nitrous Oxide) refers to the Direct and indirect emissions arising from N application (i.e. nitrous oxide, ammonia, nitrogen oxide, and nitrate). "Impacts from Soy" refer to the life cycle environmental impacts allocated to the subsequent crop in a rotation. "Manure" refers to the fertilizer production and transportation of N, P, and K nutrients. "Mineral Amendments" refers to extraction and transportation of mineral amendment application. "Cover Crops" and "Green Manures" refer to the impacts associated with growing and incorporating such crops. "Seed" refers to the activities associated with producing seeds upstream. "SOC Sequestration (CO_2)" refers to the net negative change in the soil carbon, reported as CO_2. "Net Emissions" refers to the difference between environmental impacts and SOC sequestration.

3.4.4 Climate Change Impacts by Yield

To determine if yields were a driver of emissions, the median yield of each field crop was used to differentiate “low yield” (yield below the median) from “high yield” farms. Median yields for wheat, corn, and soybeans were 3.9 t ha^{-1}, 10.1 t ha^{-1}, and 2.8 t ha^{-1}. Results are shown in Table 3-10. See Appendix X for all key contributing parameter to total CCLT impacts by median yield.

For wheat, higher yields were associated with higher CCLT impacts (740 kg CO_2 eq per tonne crop harvested) compared to the wheat with lower yields (400 kg CO_2 eq per t crop harvested). However, the low yielding wheat was associated with higher impacts from nutrient application, field operations, and seed, as well as a larger SOC change. The low yielding organic wheat was associated with greater impacts from green manures, and to a less extent manure, which may be a driver of higher N_2O emissions (Figure 3-13). Importantly, the lower yielding organic wheat applied greater amounts of N, which is likely related to a higher SOC change and the lower overall CCLT total (Table 3-10). While the total CCLT impact for the high wheat yield is larger when SOC change is included, the total excluding SOC was higher for the lower yielding wheat (1100 kg CO_2 eq per tonne crop harvested) than the higher wheat yields (880 kg CO_2 eq per tonne crop harvested). The low yielding organic wheat results that exclude the outlier presents similar findings.

Similarly, for corn farms with higher yields, there were higher total CCLT impacts (280 kg CO_2 eq per t crop harvested) than those with the lower yields (110 kg CO_2 eq per t crop harvested) (Table 3-10). The amount of applied N was higher for the farms with higher yields, and resulted in larger impacts from nutrient application. The corn farms with higher yields had higher impacts as a result of cover cropping and mineral amendments (Figure 3-13). The corn with higher yields had higher impacts as a result of growing cover crops and mineral amendment extraction and acquisition, both of which were only found for corn with higher yields (Figure 3-13). However, the corn farms with lower yield had higher N_2O emissions as well as impacts from manure acquisition (Figure 3-13). The manure applied on farms with lower corn yields contributed higher SOC sequestration per tonne crop harvested (Table 3-10). Regardless, the total CCLT impacts, with and without SOC sequestration, is higher for the corn farms with higher yields.

The soybean farms with higher yields had higher total CCLT impacts (270 kg CO_2 eq per tonne crop harvested) compared to those with the lower yields (-310 kg CO_2 eq per t crop harvested) (Table 3-10). Again, the amount of N applied was higher for the farms with higher yields, which resulted in greater impacts from nutrient application. Conversely, the farms with lower yields received very little applied N, which resulted in minimal N_2O emissions and impacts from nutrient application (Figure 3-13). Notably, soybeans with lower yields sequestered more soil carbon (-450 kg CO2 per tonne crop harvested) compared to the soybeans with higher yields (-140 kg CO_2 per tonne crop harvested) (Table 3-7). Overall, the total CCLT impacts, with and without SOC sequestration, is higher for soybean farms with higher yields.

Table 3-10 Cradle-to-harvest gate CCLT emissions associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean averaged by "low yield" and "high yield". Key contributing parameters include "Climate Impact of SOC Change" (CO_2 emissions), "Nutrient Application" (field-level nitrous oxide emissions, animal manure application, organic amendments, green manures, cover crops, impacts from leguminous crop), "Field Operations" (farm machinery using during production), and "Seed" (seed provision). "Total (Excluding SOC)" excludes contributions from SOC flux. "Applied N" is the average manure, green manure, and compost in kg N t^{-1} crop harvested associated with the yield and crop.

			Climate Change (long term) Impacts – Totals and by Farm Activity Contributions (kg CO2 eq / t crop harvested)					
Wheat	**Yield (t/ha)**	**Applied N (kg N/t crop)**	**Climate Impact of SOC Change**	**Nutrient Application**	**Field Operations**	**Seed**	**Total**	**Total (Excluding SOC)**
Low Yield	< 3.9	190	-660	930	91	40	400	1100
High Yield	> 3.9	56	-150	780	83	19	740	880
*Low Yield	< 3.9	95	-620	810	86	36	310	930
Corn								
Low Yield	< 10.1	9.7	-220	290	34	1.9	110	330
High Yield	> 10.1	20	-100	320	66	3.1	280	390
Soybean								
Low Yield	< 2.8	6.7	-450	48	66	21	-310	130
High Yield	> 2.8	31	-140	330	70	14	270	410

*Low yield average results for wheat with outlier removed

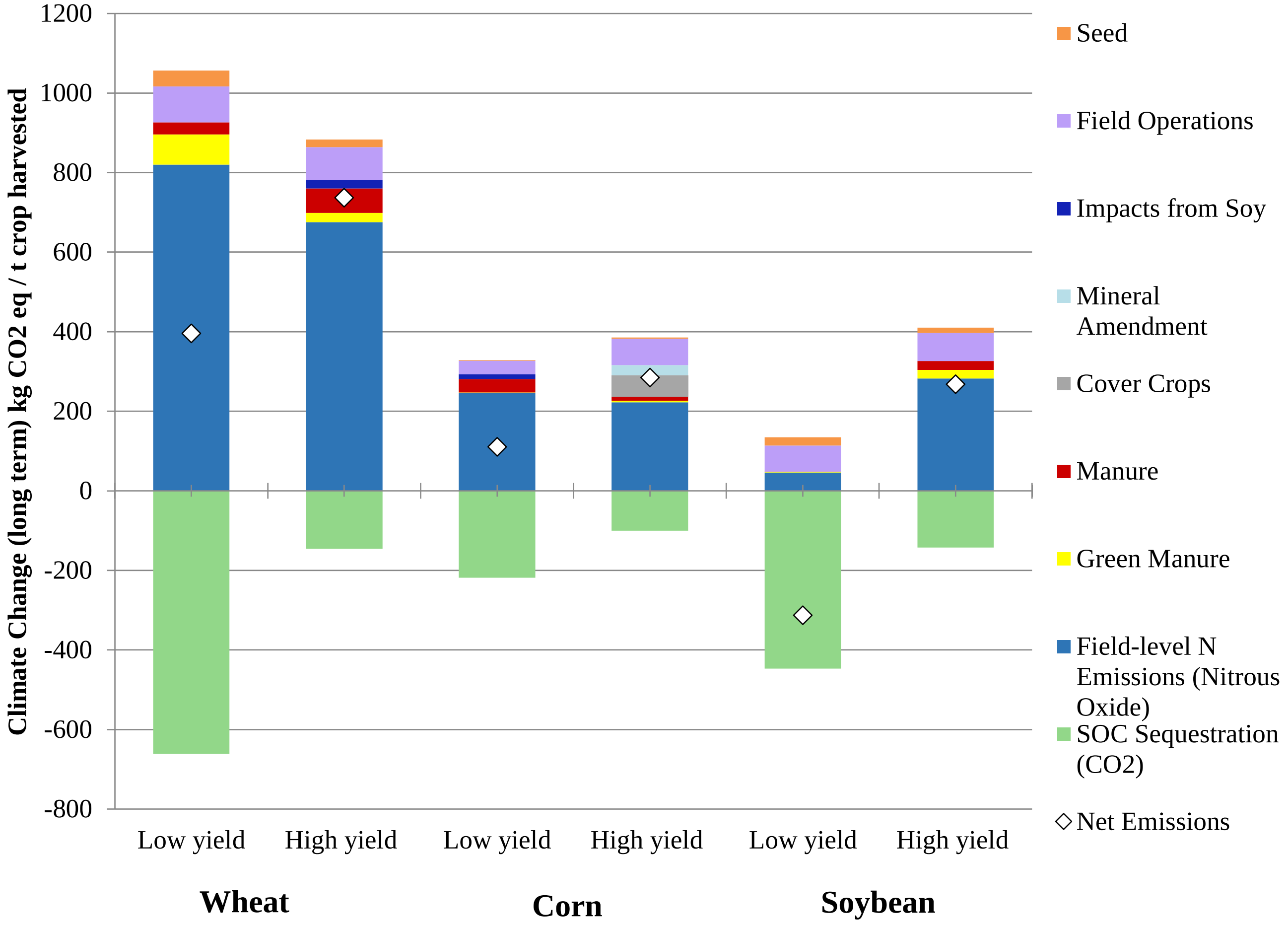


Figure 3-13 Cradle-to-harvest gate CCLT emissions associated with the production of 1 t of crop harvested of low and high yielding organic wheat (yield<3.9 t/ha or >3.9 t/ha), corn (yield<10.1 t/ha or >10.1 t/ha), and soybean (yield<2.8 t/ha or >2.8 t/ha). “Field Operations” include combine harvesting, sowing, fertilizing, rotary harrowing, rolling, offset disc harrowing, ploughing, cultivating chiseling, spring tine harrowing, hoeing, and currying (by weeder). “Field-Level N Emissions (Nitrous Oxide) refers to the Direct and indirect emissions arising from N application (i.e. nitrous oxide, ammonia, nitrogen oxide, and nitrate). “Impacts from Soy” refer to the life cycle environmental impacts allocated to the subsequent crop in a rotation. “Manure” refers to the fertilizer production and transportation of N, P, and K nutrients. “Mineral Amendments” refers to extraction and transportation of mineral amendment application. “Cover Crops” and “Green Manures” refer to the impacts associated with growing and incorporating such crops. “Seed” refers to the activities associated with producing seeds upstream. “SOC Sequestration (CO_2)” refers to the net negative change in the soil carbon, reported as CO_2. “Net Emissions” refers to the difference between environmental impacts and SOC sequestration.

3.4.5 Sensitivity Analysis

A sensitivity analysis is a crucial tool in LCA studies used to study the robustness of results and their sensitivity to parameters with high data uncertainty or variability. As a result, three parameters with high uncertainty were identified: SOC change; nitrogen emissions and the influence of emission factors; and the green manure allocation method. Given these uncertainties, three sensitivity analyses were conducted. First, the spin-up period in the SOC modelling software, Holos, was tested at 5 years and 20 years, then compared with the results under default conditions (15 years) (Section 3.4.5.1). Next, based on the uncertainty concerning the emission factors, baseline conditions were compared against a 20% and 50% increase and decrease in the emission factors used for modelling all N-related emissions (Section 3.4.5.2). Furthermore, an additional test was conducted using a global direct nitrous oxide emission factor for organic inputs based on a meta-analysis by Charles et al. (2017) (Section 3.4.5.2). Last, considering the assumption that leguminous nitrogen is available to all subsequent crops until the next leguminous crop in rotation, a sensitivity analysis tests 100% allocation of impacts and nitrogen to the subsequent crop in rotation (Section 3.4.5.3). All of the sensitivity analysis results were tested on CCLT baseline conditions and were reported using weighted averages and percent differences.

3.4.5.1 Soil Organic Carbon Spin-up Period

Table 3-11 presents results of a sensitivity analysis in which baseline CCLT impact results are compared against results from a 5-year spin-up period and 20-year spin-up period. The default spin-up period in Holos was 15 years. SOC sequestration rates increased under a 5-year spin-up period for the organic wheat (-17%), corn (-13%), and soybeans (-26%) compared to baseline SOC changes (Table 3-12), therefore decreasing CCLT impacts for organic wheat (-15%), corn (-10%), and soybeans (-61%) compared to baseline conditions (Table 3-11). Conversely, SOC sequestration rates decreased under a 20-year spin-up period for the organic wheat (+4.0%), corn (+13%), and soybeans (+4.0%) compared to baseline SOC changes (Table 3-12), resulting in an increase in CCLT impacts for organic wheat (+4.0%), corn (+10%), and soybeans (+9.0%) compared to baseline conditions (Table 3-11). Therefore, impact results are sensitive to changes in the spin-up period. Furthermore, organic soybeans were more sensitive to the 5-year spin-up period than the organic wheat and corn because less farms were losing CO_2 emissions to the atmosphere, thus, also leading to reduced direct nitrous oxide emissions compared to baseline CCLT conditions.

Table 3-11 Sensitivity of baseline (15 year spin up) CCLT impact results to a 5-year spin-up and 20-year spin-up period (kg CO_2 eq / t crop harvested).

Climate Change (long term)					
	15-yr spin-up (kg CO2 eq/ t crop harvested)	**Spin-up Period (kg CO_2 eq/ t crop harvested)**		**Difference between baseline results and the change in spin-up period (%)**	
Crop	Baseline	5-yr Spin-up	20-yr Spin-up	%Δ 5-yr spin-up	%Δ 20-yr spin-up
Wheat	520	440	540	-15	4.0
Corn	200	180	220	-10	10
Soybean	110	43	120	-61	9.0

Table 3-12 Sensitivity of baseline SOC change results to a 5-year spin-up and 20-year spin-up period (kg CO_2 / t crop harvested).

SOC change parameter, Climate Change (long term)					
	15-yr spin-up (kg CO_2 / t crop harvested)	**Spin-up Period (kg CO_2 / t crop harvested)**		**Difference between baseline SOC change results and the change in spin-up period (%)**	
Crop	Baseline	5-yr Spin-up	20-yr Spin-up	%Δ 5-yr spin-up	%Δ 20-yr spin-up
Wheat	-470	-550	-450	-17	4.0
Corn	-160	-180	-140	-13	13
Soybean	-230	-290	-220	-26	4.0

3.4.5.2 Emission Factor

Table 3-13 presents the sensitivity of baseline total CCLT results to changes (by +/- 20% and +/- 50%) in the direct and indirect nitrous oxide emission factors (total CCLT and sensitivity analysis results include SOC change). Impact results were very sensitive to the changes in the EFs. A 20% change in the EFs caused a 31% increase and 29% decrease in baseline organic wheat results, a 25% increase and decrease in baseline organic corn results, and a 36% increase and 43% decrease in baseline soybean results. Similarly, a 50% change in the EFs resulted in a 75% increase and 73% decrease in baseline wheat results, a 50% increase and 58% decrease in corn results, and a 91% increase and 102% decrease in soybean results. Thus, the results for soybeans were the most sensitive to changes in the EFs, followed by organic wheat and corn.

Table 3-13 Sensitivity of baseline CCLT results to +/- 20% and +/- 50% changes in direct and indirect nitrous oxide emission factors (Baseline and sensitivity results expressed in kg CO2 eq / t crop harvested; difference between sensitivity results and baseline expressed as a percentage (%)).

Climate Change (long term)									
	kg CO_2 eq / t crop harvested	**+/- 20% and +/- 50% change in EFs (kg CO_2 eq / t crop harvested)**				**Difference between baseline results and EF change (%)**			
Crop	Baseline	-20%	+20%	-50%	+50%	Δ -20%	Δ +20%	Δ -50%	Δ +50%
Wheat	520	370	680	140	910	-29	31	-73	75
Corn	200	150	250	84	320	-25	25	-58	50
Soybean	110	63	150	-2.3	210	-43	36	-102	91

Table 3-14 presents the sensitivity analysis of baseline CCLT results to the use of global direct nitrous oxide EF for organic inputs of 0.57% (vs. 1.7% for Ontario and 2.3% for Quebec) based on data from Charles et al. (2017) (total CCLT and sensitivity analysis results include SOC change). Baseline CCLT results were very sensitive to this EF, which only affected contributions from organic inputs of nitrogen, thus only influencing direct nitrous oxide emissions. CCLT impacts for wheat, corn, and soybeans decreased by 91%, 62%, and 106%, respectively. The biggest sensitivity was for soybeans due to very low external organic N inputs. These sensitivity results are comparable and follow a similar trend to the output from a 50% decrease in the EFs demonstrated in Table 3-13.

Table 3-14 Sensitivity of CCLT baseline results to Charles et al. (2017) global direct nitrous oxide EF for organic inputs (Baseline results and sensitivity results expressed as kg CO_2 eq/ t crop harvested; difference between sensitivity results and baseline results expressed a percentage (%)).

Climate Change (long term)			
	Baseline results vs. Sensitivity results (kg CO_2 eq / t crop harvested)		**Difference between baseline results and Organic N Input EF (%)**
Crop	Baseline	Organic N Input EF[1]	%Δ
Wheat	520	46.0	-91
Corn	200	77	-62
Soybean	110	-6.6	-106

[1]from Charles et al. (2017)

3.4.5.3 Green Manure Allocation Method

Baseline CCLT impact results were not sensitive to a change in the green manure allocation method. Organic wheat and soybeans remained unaffected by this change because the green manures in rotation were already supplying 100% of the nitrogen and production-related impacts to the wheat and soybean crops affected. However, organic corn models that were once receiving a fraction of the N and production-related impacts were now inheriting 0% from a prior leguminous crop in rotation. Therefore, baseline impact results went from 201.5 kg CO_2 eq per t crop harvested to 196.8 kg CO_2 eq per t crop harvested, resulting in only a 2.3% decrease in baseline CCLT impact results for corn. Although when expressed to two significant figures, the difference between baseline CCLT impact results and a change in the green manure allocation method were negligible (i.e. 200 kg CO_2 eq per t crop harvested).

3.5 Implications of Findings

The objective of this Canadian organic field crop LCA is to characterize the environmental profile of organic wheat, corn, and soybeans in Ontario and Quebec and understand the underlying drivers of the impacts. This study contributes to the field of LCA of organic systems by elucidating the main hotspots of organic field crop production in Eastern Canada, the influence of yields and regional differences, as well as the SOC sequestration potential, and as a result, such findings are a first step in understanding how to improve organic farming practices and reduce overall impacts.

It was expected that lower yields and regional differences would affect impacts because yield as well as climatic conditions, the surrounding geology, and soil type can influence the productivity and efficiency of agricultural production systems (Moudry et al., 2018). In reality, regional differences can also influence yields, so the interactions are more complicated than could be evaluated based on this study. However, the results suggest that impacts were driven by the combined effects and heterogeneity in management practices, yield, provincial production conditions, and soil carbon dynamics observed across the Eastern Canadian farms in this study.

Field emissions due to N fertilizers and amendments were the most significant contributors to CCLT, freshwater acidification, and eutrophication. These emissions were driven by applied organic inputs such as livestock manure and mineral amendments, as well as N supplied by leguminous crops. Emissions from nutrient application are a well-cited source of impacts in organic crop LCAs (Pelletier et al., 2008; Gonzales-Garcia et al., 2021; Hoffman et al., 2018; Chiriaco et al., 2017; Moudry et al., 2013). Often higher yields result in lower emissions on a relative basis, but it is possible that N was being applied in excess of plant needs driving higher emissions, especially from wheat production. The optimal rate of applied nitrogen to meet wheat demands is approximately 100 kg N ha^{-1} (OMAFRA, 2013), while the average applied N for wheat across all farms in this study (n= 9) was 424 kg N ha^{-1} (Table 3-7). Excessive N application cause significant N losses to the environment (Stockdale et al., 2002) and was likely the reason for higher environmental impacts related to wheat production, especially from Quebec (Table 3-9).

The nutrient requirements for corn (160 kg N ha^{-1}, OMAFRA, 2022) were comparable to the average N applied across all Eastern Canadian farms in this study (n=10) (150 kg N ha^{-1}, see Table 3-7). However, average applied N rates from Ontario and Quebec farms in this study were very different from corn N requirements, 190 and 92 kg N per hectare, respectively (Table 3-7).

Furthermore, nitrous oxide emissions were higher in Quebec than Ontario (Appendix Y), likely due to differences in soil conditions and fertilizer types, particularly the higher presence of cover crops and green manures incorporated in Ontario corn production (Appendix Y) that may have supported reduced nutrient losses to the environment (Fowler et al., 2010).

Soybeans have higher N requirements (200-260 kg N per hectare) (Manitoba Pulse and Soybean Growers, 2019), but biological N fixation supplies 75% of their required N while the rest is acquired from soil N reserves (Bohner et al., 2013). While external N is not required for soybeans, N can be applied at approximately 56 kg N per hectare (Manitoba Pulse and Soybean Growers, 2019), if needed. In this study, the average N applied across all Eastern Canadian farms (n=14) was 57 kg N per hectare (Table 3-7). The environmental impacts related to soybeans were the lowest of all field crops, likely due to lower applied N. But, differences in average N applied to Ontario and Quebec soybeans, 43 and 84 kg N ha^{-1}, respectively, resulted in higher nitrous oxide emissions from Ontario, possibly driven by lower provincial yields and N applied in excess of the crop's needs in Ontario.

The CCLT impacts by yield suggested that higher yields were correlated with larger total CCLT impacts, which was not as expected. However, several organic LCA studies demonstrated a varied relationship between yield and total GWP (Williams et al., 2010; Moudry et al., 2018; Rebolledo-Levia et al., 2022; Knudsen et al., 2014; Guareshi et al., 2019; Kamali et al., 2017) influenced by management practices, soil carbon changes, field N emissions, and production location.

In this study, the majority of Quebec-based farms were situated along the St. Lawrence River within the St Lawrence Lowlands region while a majority of Ontario farms were located further south-west and –east near Lake Ontario and Lake Huron (Great-Lakes Lowlands). Despite rapid urbanization, the St. Lawrence Lowlands have been under agricultural management since the 18th century. The St. Lawrence lowlands are characterized by its clay soil type, but the combination of fine-textured soil, humid climate conditions, less precipitation, short growing season, and heavy machinery use has led to issues of soil compaction in Quebec (Angers et al., 2022; Bryce et al., 2010). These are potential reasons for lower yields in Quebec compared to Ontario. Furthermore, despite the positive correlation between clay soils and soil organic carbon sequestration (Li et al., 1994), increased land area dedicated to annual cropping at the expense of perennial systems have resulted in significant soil organic carbon losses and degraded soil structure (Angers et al., 2022). Therefore, increased green manure growth and carbon-rich manure applied to the organic cropping systems could have improved soil C dynamics observed in Quebec in this study. Although, poorly drained soils and the excess use of manure and other fertilizers in Quebec, has led to concerns of excess P loading and large N_2O emissions, especially in the St. Lawrence Lowlands (Angers et al., 2022), as demonstrated in the results of this study.

Organic farms from Ontario were primarily located in the Mixedwood Plains Ecozone, in which a large portion has been converted to agriculture (Appendix P). The clay soils of the far and central southwest, Niagara region above the Niagara escarpment, and the Ottawa valley are dominated by soybeans, grain corn, and winter wheat (Saurette et al., 2021). These soils are well-drained, which benefits yield potentials and reduces soil and nutrient loss, which was observed for Ontario farms in this study.

Based on the agro-climatic differences of Ontario and Quebec, nutrients should be applied considering the underlying soil type and structure, rainfall, land management history, and crop requirements. Soil tests are recommended so farmers can adjust management practices based on the conditions of their farm. In addition, reduced rates of N (Laporte et al., 2021), and instead, optimized rotations, such as corn-soy and leguminous crops in rotation that benefit soil fertility and crop-specific demands.

In this analysis, soil organic carbon sequestration was an underlying driver of positive environmental contributions, but it did not offset or neutralize total production emissions. Advocates of regenerative agriculture, which is a farming system similar to the principals of organic agriculture, claim it to be a climate change mitigation strategy that can remove carbon dioxide from the atmosphere, sequester vast quantities of carbon, and offset production emissions (Ranganthan et al., 2020; Newtonne et al., 2020). While several farms in this analysis incorporated “regenerative practices”, such as manure additions, crop residue returns, green manure and cover crop planting, and diverse crop rotations, which supported carbon sequestration, these management practices also contributed greatly to higher field emissions and environmental impacts. In addition, according to an analysis by Bolinder et al. (2008), eastern ecoregions require a higher annual C input to soil to maintain SOC contents and carbon steady-states. Therefore, organic systems, as well as regenerative production, do have the potential to store carbon and benefit the natural environment, however, offsetting life cycle production emissions is unclear and practically challenging.

This analysis used country-specific Tier 2 soil N_2O emission factors to estimate N lost directly as N_2O and indirectly as N_2O due to volatilization and leaching, NH_3, NO_x. Although Tier 2 emission factors used in this analysis were specific to Canadian conditions, the current N_2O EFs don't account for differences in N_2O emissions from organic amendments and how it varies across soil types, farm management practices, and agro-climatic conditions (Charles et al., 2017). Charles et al. (2017) conducted a global meta-analysis of N_2O EFs from agricultural soils receiving organic amendments and yielded a global EF for all organic sources equal to 0.57 (+/- 30%), which is lower than the recommended global default N_2O EF of 0.01 kg N_2O-N per kg N (1%). CCLT results using the EF reported from Charles et al. (2017) found that results were nearly equivalent to reducing the IPCC Tier 2 EFs by 50%. Therefore, without highly accurate and representative EFs, N_2O emissions could be greatly overestimated, especially in organic production systems.

3.6 Conclusion

The cradle-to-harvest gate environmental impacts of organic field crop production in Eastern Canada were assessed using field-level data supplied by farmers in Ontario and Quebec. The results reveal that across all impact categories included in this analysis, except for land occupation (biodiversity), Eastern Canadian organic wheat had the largest impact per tonne of crop harvested, followed by corn and soybeans. The main contributor to environmental impacts, specifically CCLT, acidification, and eutrophication, across all crops were field emissions from N fertilizers and amendments such as livestock manure and mineral amendments, as well as N supplied by leguminous crops. While higher yields often result in lower emissions on a relative basis, it is likely that N was being applied in excess of plant needs, thus driving higher emissions, especially from wheat production. Furthermore, differences in the agro-climatic conditions between Quebec and Ontario, such as precipitation levels, soil type, and land management history, possibly influenced the productivity and total environmental impacts of organic crop production. An underlying driver of positive environmental contributions was soil organic carbon sequestration, observed under wheat, corn, and soybean production, but it did not offset nor neutralize the climate impacts. However, quantifying soil organic carbon addresses significant knowledge gaps regarding the carbon sequestration potential of organic systems in Canada as well as the lack of soil carbon data in organic agricultural LCA studies. Therefore, diverse management practices such as green manure incorporation, cover cropping, and carbon-rich manure application, are recommended as continued support for carbon accumulation, but nutrients should be managed carefully and consider the crop's needs, as well as the underlying agro-climatic conditions of production to prevent losses to the environment.

The results and interpretations presented in this analysis are limited by a small sample size of Eastern Canadian field crop farms. Given a larger sample of farms, future research directions should explore the influence of specific management practices on environmental impacts and changes in soil carbon, especially under region-specific production conditions. This research could enable targeted emission reduction management strategies and a better understanding of the quantitative relationship between management practices and soil carbon sequestration in Canada. Furthermore, the lack of organic field crop LCAs that include soil organic carbon changes and similar methodology limit comparative results, and so more organic LCA research that includes soil carbon is needed to corroborate results presented in this analysis and improve understandings of C dynamics in organic systems. In addition, CCLT impact results were significantly sensitive to changes in the N_2O emission factors. While this analysis used representative and well-established EFs from IPCC Tier 2 methodology, future organic LCAs require N_2O EFs that reflect different organic sources, and specific local and regional conditions to gain a more accurate understanding of nitrous oxide emissions from organic production systems.

Based on these results, and in their current state, organic field cropping systems in Eastern Canada are not climate neutral, and potentially contribute to other negative environmental impacts. Further organic LCA research, based on the methodological foundation established in this analysis, is necessary to advance understandings of GHG emission dynamics, establish soil carbon sequestration strategies, and work towards improving the efficiency and productivity of organic systems so that they can, one day, be of scale to address the climate crisis.

Chapter 4 Implications and Conclusions from the Research

Through an analysis of the practices that increase SOC and LCA based on organic field crops in Ontario and Quebec, it was found that nutrient application management practices substantially affect soil organic carbon changes and N_2O emissions. Management practices such as crop rotation diversity, crop residue retention, green manures and cover crops, reduced tillage operations, organic amendments (i.e. livestock manure and compost), as well as a combination of practices demonstrated positive influences on SOC stocks across organic and conventional field crop farms in the northern temperate zone of the globe (Chapter 2). Such practices were also employed in several of the organic field crops farms across Eastern Canada included in this analysis, which likely supported the soil organic carbon sequestration observed from the production of wheat, corn, and soybeans across Eastern Canadian farms (Chapter 3). However, field N emissions from nutrient application practices were also the main contributor to negative environmental impacts. Studies of SOC alone don't often account for nitrogen emissions, and as a result, looking at SOC rates alone do not provide a good picture of the overall GHG impacts from agricultural production systems.

Based on the findings in this analysis and the methodological foundation established, future organic LCA research should assess the influence of soil organic carbon changes and N_2O emissions from specific management practices on net GHG performance, especially considering differences in region-specific agro-climatic production conditions. SOC changes, N_2O emissions, and environmental factors are closely intertwined, and so a better understanding of their relationship within agricultural systems can help yield effective GHG emission mitigation strategies.

The dynamics of organic production systems, especially as a potential climate-friendly alternative to conventional production systems, must continue to be analyzed to understand their environmental impacts, particularly their GHG performance and soil organic carbon sequestration potential. Such information may reveal how organic systems, as well as their conventional counterparts, can be improved to meet climate-related goals and better support the natural environment, particularly in Canada where agriculture is a well-established and expanding sector.

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Appendix A

QUESTIONNAIRE QUESTIONS

CONTACT INFORMATION

Please provide **your name, the name of your farm or business, and your contact information** (email address, phone number, and mailing address) below. It will only be used to follow up with you if any further clarification is needed.

Name: ____

Business name: ____

Email: ____

Phone number: ____

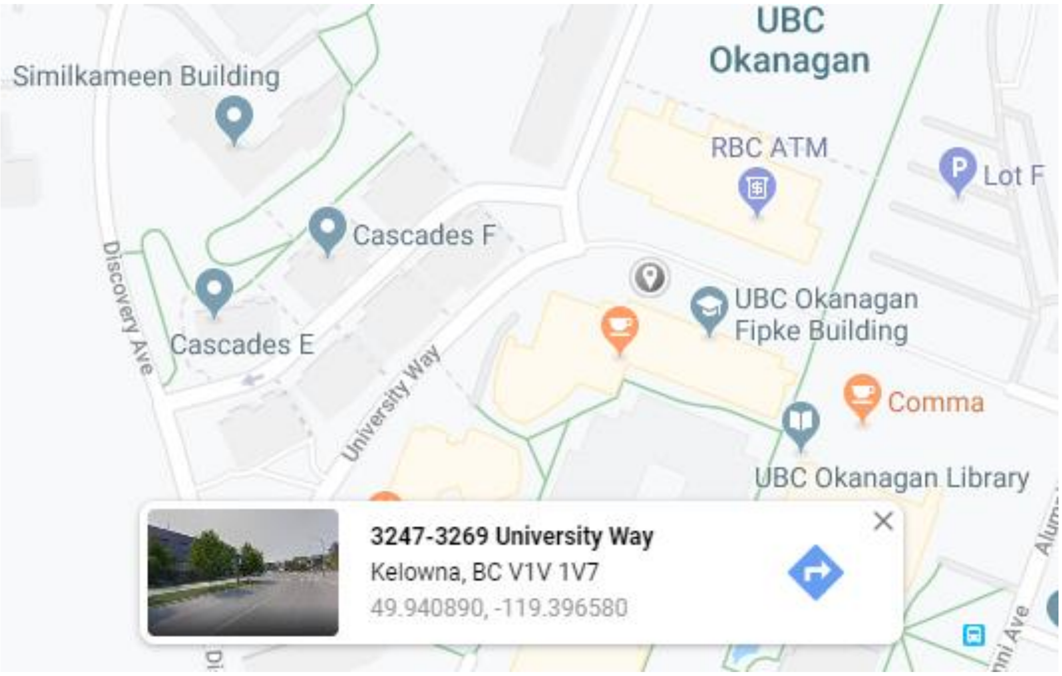
Mailing address: ____

PHYSICAL LOCATION DATA

In order to determine geographical soil and climate data for your farm, please provide **latitude and longitude coordinates for the location of your farm**, OR the **legal land description**.

The latitude and longitude can be found on Google Maps by right clicking on the location and selecting "What's here?" and the location with latitude and longitude coordinates will pop up. Alternatively, on mobile, touch and hold the location on the map and the coordinates will come up.

E.g. latitude: 49.940890, longitude: 119.396580



3247-3269 University Way
Kelowna, BC V1V 1V7
49.940890, -119.396580

Legal land descriptions are written as in the following example: SW 24-38-20-W5 representing Southwest Quarter of Section 24, Township 38, Range 20, West of the 5th Meridian.

Latitude: ____

Longitude:

____

Legal land description: ____

LAND USE PRACTICES

What type of organic certification does your farm have?

____

If not formally certified, what attributes of organic agriculture does your farm have?

____

How long has your farm been under the current organic management practices?

____

What was the previous land use or management type on the farm before the current practices?

____

How long was the land under these previous management practices, or land use type (if known)?

____

BEFORE YOU BEGIN

Please indicate which crop you will focus on for this survey: ________________________

*****Please note that the crop selected for this survey is the crop for which you will provide the following data. Each new or different crop requires a separate survey.

CROP INVENTORY

Seeding rate, yield and rotation

Please indicate the **crop rotation, and the seeded area, seeding rates and yields of each crop**. Fill in one row per crop in your rotation. Include any **cover crops, catch crops or green manure** grown. If you are filling in *multiple questionnaires* (if you grow more than one of the following crops: wheat, oats, barley, rye, potatoes, peas, soybeans, lentils and corn), you *only need to fill in this table once*, with *all crops in your rotation*.

Crop	**Year grown**	**Length in rotation (months or years)**	**Timing (months or seasons grown)**	**Seeded area (acres or ha)**	**Seeding rate (e.g. bu/acre or lb/acre)**	**Yield (e.g. t/acre, bu/acre, lb/acre)**

Please indicate the fate (i.e. **method of destruction, or incorporation**) of all **cover crops, catch crops, ley, green manure**, etc. produced. As well, please indicate the fate of any **crop residues** produced, as well as the amount produced (if known). Please indicate the **units of measurement** when applicable.

Cover crops: _________________________ Catch crops: _________________________

Ley: ___________________________ Green manure: _________________________

Crop residues: ____

Nutrient application

Please indicate, for each product applied in the most recent production year to supply nutrients, the type (i.e. **type of fertilizer, type of manure, type of compost, green manure crop type**, etc.), **product name** (if applicable), **application rate**, **nutrient composition** (N/P/K/S, or other),

application method, **area applied** (either total acres, or percent of total farm area), and **timing** (month or season applied). Please indicate the **units of measurement** when applicable.

Type, and product name (if applicable)	Application rate of product (lb/acre or ga/acre or L/acre)	N/P/K/S composition (% or lbs)	Other nutrient composition (% or lbs)	Seeded area applied (% or acres)	Timing (month or season applied)

Plant protection

Please indicate, for each product applied in the most recent production year for plant protection (i.e. **herbicide, insecticide**), the **type of product**, **product name** (if applicable), **application rate**, **active ingredient** (if applicable), **application method**, **area applied** (either total acres, or percent of total farm area), and **timing** (month or season applied). Please indicate the **units of measurement** when applicable. Note that any mechanical plant protection should be described in the farm operations section below.

Type, and product name (if applicable)	Application rate of product (lb/acre or ga/acre or L/acre)	Active ingredient (if applicable)	Seeded area applied (% or acres)	Timing (month or season applied)

Irrigation

Please indicate the **amount of irrigation water** applied in the most recent production year, and the **method of irrigation** (e.g. drip, sprinkler, etc.). Please indicate the **units of measurement** of irrigation water.

Amount of water applied: ____________________________ Units: ________________________

Method of irrigation: ____

Field operations

Please fill out **as many text boxes as possible in a row**, for all field operations on your farm. Fill out each row for the **field operations listed that are performed on your farm**, and add rows for any **other operations**. Please also indicate the **depth of tillage**, if applicable. In order to avoid double-counting, please indicate any operations that were **done in combination**, and only fill in the row of machinery and fuel information for those combined operations **once**. Please indicate the **units of measurement** when applicable.

Field operation	**Area applied (% or acres)**	**Machinery used (brand/make)**	**Frequency (yearly, twice a year, once every 2 years, etc.)**	**Timing (month or season applied)**	**Machinery fuel use (L/hr or ga/hr)**	**Area covered by machinery per hour (acre/hr or ha/hr)**	**Indicate other operation(s) combined with this operation**
Tillage, depth: __________							
Ploughing							
Disking							
Harrowing							
Seeding							
Land rolling							
Fertilizer application							
Pesticide application							
Weeding							
Hoeing							
Harvesting							
Biomass burning							

Post-harvest

Please indicate the following information regarding the post-harvest **grading, drying, cooling and storage** of crops:

Grading: Please indicate the amount of crop yield graded, the machinery used, the hours of machinery use, and the fuel use (if applicable and known). Please indicate the **units of measurement** when applicable.

Crop	**Amount graded (bushel or % of total yield)**	**Machinery used (brand/make)**	**Hours of machinery use**	**Fuel use of machinery (L/hr or ga/hr)**

Drying: Please indicate the amount of crop yield dried, the fan model and size, the hours of fan use, and the energy requirements of the fan (if known). Please indicate the **units of measurement** when applicable.

Crop	**Amount dried (bushel or % of total yield)**	**Fan used (brand and size)**	**Hours of fan use**	**Energy use of fan (kWh)**

Cooling: Please indicate the amount of crop yield cooled, method of cooling, the hours of machinery use, and the energy requirements of the cooling operation (if known). Please indicate the **units of measurement** when applicable.

Crop	**Amount cooled (bushel or % of total yield)**	**Method of cooling**	**Hours of cooling**	**Energy use of cooling**

Storage: Please indicate the amount of crop yield stored, storage infrastructure type and size, length of storage, any temperature or ventilation control, and the energy requirements of the storage operation (if known). Please indicate the **units of measurement** when applicable.

Crop	**Amount stored (bushel or % of total yield)**	**Storage infrastructure (type and size)**	**Length of storage**	**Ventilation, temperature control, etc. included**	**Energy use of storage**

Preamble

We are also interested in the potential effect that farmer characteristics including demographic information, knowledge, experience, motivations and worldview could have on factors that affect the greenhouse gas emissions of agriculture. The questions below will help inform this part of our analysis:

Personal Characteristics

1. What age group do you belong to?
- 18 to 29
- 30 to 39
- 40 to 49
- 50 to 59
- 60 +

2. What is your gender?
- Male
- Female
- Other (specify) _______________
- Prefer not to answer

Experience

3. What is the highest level of education you have completed?
- Some high school
- High school
- University degree
- College/Trade School
- Master's degree
- PhD or higher
- Prefer not to answer
- Not applicable

4. If your education extended beyond high school, was any of it in agriculture? Select all that apply
- University degree
- College/Trade School
- Master's degree
- PhD or higher
- Degree wasn't in agriculture *****
- Prefer not to answer

*****If your degree was not in agriculture, please specify:

  - Arts and humanities
  - Architecture
  - Business and management studies
  - Social sciences

- Natural sciences
- Ecology and environmental studies
- Education
- Medicine
- Law
- Engineering and technology
- Computer science and information systems

5. If you have had any formal or informal training related to agriculture, select all that apply.
- Agricultural training program
- Apprenticeship
- Prior employment on someone else's farm
- Workshops
- Member of agriculture organization(s)
- Webinars
- Seminars/Conferences
- Other

6. How many years have you operated a farm?
- 0-5 years
- 6-10 years
- 11-20 years
- 21 - 30 years
- 31-40 years
- 40+ years

7. Which of the following best describes your farming experience when you grew up?
- Did not grow up on any type of farm
- Grew up on a commercial farm
- Grew up on a subsistence farm (for the sole purpose of feeding my family)
- Grew up on a hobby/small-scale farm, e.g, market garden for local community

Qualifications

8. Does your farm have an organic certification?
- Yes, I am certified organic*
- No, I am not certified organic

*If you have an organic certification, please specify:

- Bioagricert S.R.L. Unipersonale
- British Columbia Association for Regenerative Agriculture (BCARA)
- CCOF Certification Services Limited Liability Company
- CCPB Srl
- Centre for Systems Integration (CSI) (a division of the Canadian Seed Institute)
- Ecocert Canada
- Fraser Valley Organic Producers Association (FVOPA)
- International Certification Services Incorporated (ICS)
- LETIS S.A.
- Organic Crop Improvement Association (OCIA)
- Organic Producers Association of Manitoba Co-operative Incorporated (OPAM)
- Organisme de Certification Québec Vrai (OCQV)
- Pacific Agricultural Certification Society (PACS)
- Pro-Cert Canada
- Quality Assurance International Incorporated (QAI)
- Quality Certification Services (QCS)
- TransCanada Organic Certification Services (TCO Cert)
- Other (please indicate): ___________________________

9. If you answered ‘yes’ to (8), how many years has your farm had an organic certification?

- Not certified
- 0-5 years
- 6-10 years
- 11-19 years
- 20 or more years

10. How many years have you been farming organically, whether or not you have received an organic certification?

- Not certified
- 0-5 years
- 6-10 years
- 11-19 years
- 20 or more years

11. Below is a list of potential motivators for farming organically. For each, please indicated their relative importance to you in your decision to farm organically.

- *To improve the profitability of my farm operation and increase income*

    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I'm concerned about the potential negative impacts that conventional farming can have on the environment, e.g., impact of synthetic pest and weed control measures*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Education and/or other available information has informed my decision*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I want to ensure that my farm can withstand drought, pests, invasive species, etc*.
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Farming is an enjoyable way of life*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I consider myself a steward of the land*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I have environmental concerns*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important

    - Very important
- *Food quality is important to me*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I hold membership in farming organizations that support organic agriculture*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *It is better for the health of farmers, family, livestock, and consumers*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Organic farming aligns with my values, e.g., I value healthy ecosystems, working with nature, and supporting human and animal health*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Organic farming aligns with my beliefs, e.g., I believe agriculture impacts the environment and it is our responsibility to care for the land*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Organic farming aligns with my spiritual beliefs*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Organic farming has been in my family for many generations*
    - Not important at all

    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Other motivators*

12. How important is reducing greenhouse gas (GHG) emissions in your farm management practice?
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important

13. Whether or not you employ them, how important do you think the following strategies or activities are for reducing GHG emissions from farms?

- *Applying integrated pest management*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Converting marginal crop land to perennial grass or trees*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Crop protection strategies*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Crop residue management*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important

  - Very important
- *Crop rotations and crop diversity*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Integrating livestock and crops*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Natural/non-chemical forms of fertilizer application*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Planting shrubs and trees as shelterbelts*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Reducing on farm fossil fuel usage*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Reducing fallow periods*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Reduction in tillage*
  - Not important at all
  - Slightly important
  - Important

  - Fairly important
  - Very important
- *Restoring degraded land, improving pasture management*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Restoring wetlands*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Soil conservation strategies*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Using legumes and/or grasses in crop rotations*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Using rotational grazing and high-intensity/short-duration grazing*
  - Not important at all
  - Slightly important
  - Important
  - Fairly important
  - Very important
- *Other*

14. For each of the activities or strategies listed below, please indicate whether you employ them on your farm to reduce GHG emissions

- *Applying integrated pest management*
  - Yes
  - No
- *Converting marginal crop land to perennial grass or trees*

  - Yes
  - No
- *Crop protection strategies*
  - Yes
  - No
- *Crop residue management*
  - Yes
  - No
- *Crop rotations and crop diversity*
  - Yes
  - No
- *Integrating livestock and crops*
  - Yes
  - No
- *Natural/non-chemical forms of fertilizer application*
  - Yes
  - No
- *Planting shrubs and trees as shelterbelts*
  - Yes
  - No
- *Reducing on farm fossil fuel usage*
  - Yes
  - No
- *Reducing fallow periods*
  - Yes
  - No
- *Reduction in tillage*
  - Yes
  - No
- *Restoring degraded land, improving pasture management*
  - Yes
  - No
- *Restoring wetlands*
  - Yes
  - No
- *Soil conservation strategies*
  - Yes
  - No
- *Using legumes and/or grasses in crop rotations*
  - Yes
  - No

- *Using rotational grazing and high-intensity/short-duration grazing*
    - Yes
    - No
- *Other*

15. How important are each of the following motivations in your desire to reduce GHG emissions on your farm?

- *People in my community (e.g., residents, neighbours, local community groups), encourage me*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *It provides me with economic advantages (e.g., premium price)*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I want to get ahead of government policy and environmental regulations*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Consumers are demanding low GHG emissions from their food*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Technological advancements make it easier (conservation practices, computer modelling, etc.)*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important

- *Other members of my family managing the farm emphasize its importance*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I have read research and/or received education or information that convinced me it is the right thing to do*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I am concerned about climate change*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I believe agriculture can help to substantially reduce global GHG emissions*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Businesses, organizations, and/or associations encourage me to reduce GHG emissions*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important

Information-seeking

16. How important is it for you to stay up to date with each of the following?

- *New farming practices*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important

    - Very important
- *Agricultural policies and regulations*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Programs*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *New developments and innovations in agriculture (e.g., technology, new research)*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important

Barriers

17. How important are the following barriers to reducing GHG emissions on your farm?

- *I don't have time*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *It costs too much*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I don't have access to knowledge or training*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important

    - Very important
- *I don't have access to equipment and/or technical assistance*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I am not familiar with GHG reduction strategies*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I don't have adequate labour available on my farm*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *The labour available to me doesn't have adequate technical knowledge*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Government regulations and current policy do not adequately support/incentivize these types of practices*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *Others involved in farm management decisions are not interested*
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important
- *I already do everything I can to reduce GHG emissions on my farm, so further emissions reduction efforts are not necessary*

Appendix B

Table B-1 Modified processes used in openLCA modelling

Process	Modification
ammonia production, partial oxidation, liquid | ammonia, anhydrous, liquid |APOS, U - CA, ON	Province-specific provider for heat, district or industrial, other than natural gas; Canadian-specific provider for tap water
ammonium nitrate production | ammonium nitrate | APOS, U - CA, ON	Province-specific location; Provincial-specific provider for electricity, low voltage; Canadian-specific heat, district or industrial, natural gas
ammonium sulfate production | ammonium sulfate | APOS, U - CA, AB	Province-specific location; Rest-of-North-America provider for ammonia, anhydrous, liquid; Provincial-specific provider for electricity, medium voltage
Brown-Schlesinger process | sodium tetrahydridoborate | APOS, U - CA, MB	Province-specific location: Province-specific location for electricity, medium voltage; Province-specific provider for heat, district or industrial, other than natural gas
calcium ammonia nitrate production | calcium ammonium nitrate | APOS, U - CA, ON	Province-specific location; Provincial-specific provider for electricity, low voltage
calcium carbonate production, precipitated | calcium carbonate, precipitated | APOS, U - CA, ON	Province-specific location; Provincial-specific provider for electricity, medium voltage; Canadian-specific provider for heat, district or industrial, natural gas; Canadian-specific provider for tap water
clover seed production, Swiss integrated production, for sowing | clover seed, Swiss integrated production, for sowing | APOS, U - CA, ON	Province-specific location; Provincial-specific provider for electricity, low voltage

clover seed production, Swiss integrated production, for sowing | clover seed, Swiss integrated production, for sowing | APOS, U - CA, QC	Province-specific location; Provincial-specific provider for electricity, low voltage
Copper mine operation and beneficiation, sulfide ore | molybdenite | APOS, U - CA, QC	Province-specific location; Province-specific provider for electricity, medium voltage; Province-specific provider for electricity, high voltage
fishmeal and fish oil production; 63-65% protein, from fish residues | fishmeal, 63-65% protein | APOS, U - CA, SK	Province-specific location; Provincial-specific provider for electricity, medium voltage; Canadian-specific provider for heat, district or industrial, other than natural gas
Gypsum quarry operation | gypsum, mineral | APOS, U - CA, NS	Province-specific location; Province-specific provider for electricity, medium voltage
lentil seed production, for sowing | lentil seed, for sowing | APOS, U - CA, ON	Province-specific location; Provincial-specific provider for electricity, low voltage; Canadian-specific provider for lentil
lentil seed production, for sowing | lentil seed, for sowing | APOS, U - CA, QC	Province-specific location; Provincial-specific provider for electricity, low voltage; Canadian-specific provider for lentil
Magnesium sulfate production | magnesium sulfate | APOS, U - CA, SK	Province-specific location; Province-specific provier for electricity, medium voltage
pea seed production, organic, for sowing | pea seed, organic for sowing | APOS, U - CA, ON	Province-specific location; Provincial-specific provider for electricity, low voltage
pea seed production, organic, for sowing | pea seed, organic for sowing | APOS, U - CA, QC	Provincial-specific location; Provincial-specific provider for electricity, low voltage

pea seed production, organic, for sowing | pea seed, organic for sowing | APOS, U - CA, ON (Alfalfa)	Provincial-specific location; Provincial-specific provider for electricity, low voltage
pea seed production, organic, for sowing | pea seed, organic for sowing | APOS, U - CA, QC (Alfalfa)	Provincial-specific location; Provincial-specific provider for electricity, low voltage
phosphate rock beneficiation | phosphate rock, beneficiated | APOS, U - CA, QC	Provincial-specific location; Provincial-specific provider for electricity, medium voltage
Potash salt production | potash salt | APOS, U - SK	Province-specific location; Rest-of-World and Global for all other providers
potassium chloride production | potassium chloride | APOS, U - CA, SK	Province-specific location; Provincial-specific provider for electricity, low voltage; Provincial-specific provider for electricity, medium voltage
potassium sulfate production | potassium sulfate | APOS, U - CA, SK	Provincial-specific location; Provincial-specific provider for electricity, medium voltage; Canadian-specific provider for heat, district or industrial, other than natural gas
Rock crushing | rock crushing | APOS, U - US	US-specific location; US-specific provider for electricity, medium voltage
rye seed production, organic, for sowing | rye see, organic, for sowing | APOS, U - CA, ON	Provincial-specific location; Provincial-specific provider for electricity, low voltage
rye seed production, organic, for sowing | rye see, organic, for sowing | APOS, U - CA, QC	Provincial-specific location; Provincial-specific provider for electricity, low voltage
single superphosphate production | single superphosphate | APOS, U - CA, AB	Provincial-specific location; Provincial-specific provider for electricity, low voltage
Sodium borates production | sodium borates | APOS, U - CA, NB	Province-specific location; Province-specific provider for electricity, medium voltage; Province-specific provider for heat, district or industrial, other than natural gas
transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U, CA	Canadian-specific location; Rest-of-World provider for diesel, low-sulfur

treatment of garden biowate, home composting in heaps | compost | APOS, U - CA, ON	Provincial-specific location; Province-specific provider for electricity, high voltage; Province-specific provider for electricty, low voltage; Province-specific provider for electricity, medium voltage
treatment of garden biowate, home composting in heaps | compost | APOS, U - CA, QC	Provincial-specific location; Province-specific provider for electricity, high voltage; Province-specific provider for electricty, low voltage; Province-specific provider for electricity, medium voltage
triple superphosphate production | triple superphosphate | APOS, U - CA, AB	Provincial-specific location; Provincial-specific provider for electricity, low voltage
urea production | urea | APOS, U - CA, ON	Provincial-specific location; Provincial-specific provider for electricity, low voltage
Maize seed production, organic, for sowing | maize seed, organic, for sowing| APOS, U - CA, ON	Province-specific location; Provincial-specific provider for electricity, low voltage
Maize seed production, organic, for sowing | maize seed, organic, for sowing| APOS, U - CA, QC	Province-specific location; Provincial-specific provider for electricity, low voltage
Wheat seed production, organic, for sowing | wheat seed, organic, for sowing| APOS, U - CA, ON	Provincial-specific location; Provincial-specific provider for electricity, low voltage
Wheat seed production, organic, for sowing | wheat seed, organic, for sowing| APOS, U - CA, QC	Provincial-specific location; Provincial-specific provider for electricity, low voltage
Soybean seed production, organic, for sowing | wheat seed, organic, for sowing| APOS, U - CA, ON	Provincial-specific location; Provincial-specific provider for electricity, low voltage
Soybean seed production, organic, for sowing | wheat seed, organic, for sowing| APOS, U - CA, QC	Provincial-specific location; Provincial-specific provider for electricity, low voltage
Zinc monosulfate production | zinc monosulfate | APOS, U - CA, ON	Province-specific location; province-specific provider for heat, district or industrial, natural gas
Zinc monosulfate production | zinc monosulfate | APOS, U - CA, QC	Province-specific location; province-specific provider for heat, district or industrial, natural gas

Appendix C

Table C-1 Nitrogen (N), Phosphorus (P), and Potassium (K) values (%) of various manure sources used by farmers and their sources

Manure Type	NPK	Source	NPK	Source	NPK	Source	Average NPK
Chicken (dried)	5-1-2	The Nutrient Company (n.d.)	1.5-2.1-1.5	A&L Canada Laboratories (2013)			3.25-2.05-1.25
Chicken (pellets)	4-2.5-2.3	Allotment & Gardens (n.d.)	4-3-2	Crop Fertility Services (2018)	5-3-2	Acti-Sol. (n.d.)	4.33-2.83-2.1
Pullet (solid)	2-2-2	LCI data					2-2-2
Hen (solid)	5-3-2	Acti-Sol. (n.d.)					5-3-2
Turkey (solid)	0.89-1.7-0.75	A&L Canada Laboratories (2013)					0.89-1.7-0.75
Swine (solid)	0.29-0.49-0.57	OMFRA (2013)	0.8-0.7-0.5	Allotment & Gardens (n.d.)			0.55-0.17-0.54
Swine (liquid)	0.26-0.12-0.19	OMFRA (2013)	0.15-0.05-0.06	Lorimor et al. (2004)			0.21-0.08-0.12
Dairy (liquid)	0.16-0.09-0.25	OMFRA (2013)	0.72-0.37-0.4	Lorimor et al. (2004)			0.44-0.23-0.33
Beef (solid)	1-0.3-0.7	LCI data	3-2-1	LCI data	0.18-0.33-0.66	OMFRA (2013)	1.39-0.87-0.78

Beef (liquid)	0.15-0.08-0.23	OMFRA (2013)	0.35-0.18-0.29	Lorimor et al. (2004)			0.25-0.13-0.26
Sheep (solid)	1.15-1-0.33	The Nutrient Company (n.d.)	3.09-2.5-2.25	OMFRA (2013)	0.28-0.34-0.76	Lorimor et al. (2004)	1.51-1.28-1.11
Horse (solid)	0.7-0.3-0.6	LCI data	0.62-0.17-0.62	A&L Canada Laboratories (2013)			0.66-0.23-0.61

Appendix D

Table D-1 Nitrogen (N), Phosphorus (P), and Potassium (K) values (%) of various organic amendments used by farmers and their references

Nutrient	NPK	Source	NPK	Source	NPK	Source	Average NPK
Compost	1-1-1	University of Massachusetts Amherst (2015)	0.5-0.27-0.8	Allotment & Gardens (n.d.)	5.7-0.04-0.15	Abdul Kadir et al. (2016)	2.4-0.38-0.65
Fish Fertilizer	8.5-7.4-0	The Nutrient Company (n.d.)	4-1-1	Patterson (2021)	5-1-1	Parker (2022)	5.1-3.2-0.6
Tecmac G&G	7-4-1	LCI data	4-8-3	Slyvite (n.d.)			5.5-6-2.1
Gaia Green Feather Meal	13-0-0	Gaia Green (n.d.)					13-0-0
Azomite	0-0-0.2	Mr. Fertilizer (n.d.)					0-0-0.2
Sulpomag	0-0-20	E.B. Stone (n.d.)	0-0-22	The Fertrell Company (n.d.)	0-0-21.5	Greenway Biotech, Inc (n.d.)	0-0-21.5
K-Mag	0-0-22	Kis Organics (n.d.)					0-0-22
Soft Rock Phosphate	0-5-0	Arbico organics (n.d.)					0-5-0

Organic Hemp Seed Meal	4.5-1.2-0.9	Walla (n.d.)					4.5-1.2-0.9

Appendix E

Table E-1 Background processes and inputs to openLCA for the field operations component of modelling.

Process Modelled	**Provider**
Application of plant protection product, by field sprayer	Application of plant protection product, by field sprayer | application of plant protection product, by field sprayer | APOS, S - CA-QC
Combine harvesting	Combine harvesting | combine harvesting | APOS, S - CA-QC
Fertilising, by broadcaster	Fertilising, by broadcaster | fertilising, by broadcaster | APOS, S CA-QC
Hoeing	Hoeing | hoeing | APOS, S - ROW
Sowing	Sowing | sowing | APOS, S - CA-QC
Swath, by rotary windrower	Swath, by rotary windrower | swath by rotary windrower | APOS, S - CA-QC
Tillage, cultivating, chiselling	Tillage, cultivating, chiselling | tillage, cultivating, chiselling | APOS, S CA-QC
Tillage, currying, by weeder	Tillage, currying, by weeder | tillage, currying, by weeder | APOS, S - ROW
Tillage, harrowing, by offset disc harrow	Tillage, harrowing, by offset disc harrow | tillage, harrowing, by offset disc harrow | APOS, S - CA

Tillage, harrowing, by rotary harrow	Tillage, harrowing, by rotary harrow | tillage, harrowing, by rotary harrow | APOS, S - CA
Tillage, harrowing, by spring tine harrow	Tillage, harrowing, by spring tine harrow | tillage harrowing, by spring tine harrow | APOS, S - ROW
Tillage, hoeing and earthing-up, potatoes	Tillage, hoeing and earthing-up, potatoes | tillage, hoeing and earthing-up potatoes | APOS, S - CA-QC
Tillage, ploughing	Tillage, ploughing | tillage, ploughing | APOS, S - CA-QC
Tillage, rolling	Tillage, rolling | tillage, rolling | APOS, S - CA-QC
Tillage, rotary cultivator	Tillage, rotary cultivator | tillage, rotary cultivator | APOS, S – CA-QC

Appendix F

Table F-1 Background processes and inputs to openLCA for the seed inputs component of modelling. Seed inputs were modified to reflect both Ontario and Quebec. Rye seed is for modeling the cover crops. Pea seed and clover seed are for modeling the green manures.

Process Modelled	Provider
Maize seed, organic, for sowing	Maize seed production, organic, for sowing | maize seed, organic, for sowing | APOS, U – CA-ON
Maize seed, organic, for sowing	Maize seed production, organic, for sowing | maize seed, organic, for sowing | APOS, U – CA-QC
Soybean seed, organic, for sowing	Soybean seed production, organic, for sowing | soybean seed, organic, for sowing | APOS, U – CA-ON
Soybean seed, organic, for sowing	Soybean seed production, organic, for sowing | soybean seed, organic, for sowing | APOS, U - QC
Wheat seed, organic, for sowing	Wheat seed production, organic, for sowing | wheat seed, organic, for sowing | APOS, U – CA-ON
Wheat seed, organic, for sowing	Wheat seed production, organic, for sowing | wheat seed, organic, for sowing | APOS, U – CA-QC
Rye seed, organic, for sowing	Rye seed production, organic, for sowing | rye seed, organic, for sowing | APOS, U - ROW
Pea seed, organic, for sowing[1]	Pea seed production, organic, for sowing | pea seed, organic, for sowing | APOS, U - ROW

Pea seed, organic, for sowing	Pea seed production, organic, for sowing | pea seed, organic, for sowing | APOS, U - ROW
Clover seed, Swiss integrated production, for sowing1	Clover seed production, Swiss integrated production, for sowing | clover seed, Swiss integrated production, for sowing | APOS, U - CH

[1] Proxy for alfalfa seed

Appendix G

Table G-1 Background processes and inputs to openLCA for the nutrient application component of modeling

Process Modelled	Provider	Notes
Manure		
N Fraction Manure	Refer to Table K-1	Inputs are from producer surveys
P Fraction Manure	Refer to Table K-2	Inputs are from producer surveys
K Fraction Manure	Refer to Table K-3	Inputs are from producer surveys
Transport, freight, lorry 7.5-16 metric ton, EURO6	Transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U – ROW	Inputs are from Beef Cattle Research Council (2020)
Other Amendments		
Cover crop	Refer to Table M-1	Inputs are from producer surveys
Mineral Amendments	Refer to Table N-1	Inputs are from producer surveys
Green Manures		
Alfalfa	Refer to Table L-1	Inputs are from producer surveys
Lentils	Refer to Table L-2	Inputs are from producer surveys
Peas	Refer to Table L-3	Inputs are from producer surveys
Clover (red/yellow)	Refer to Table L-4	Inputs are from producer surveys
Emissions		
Ammonia, emission to air/low population density	Elementary Flow	Inputs are from producer surveys and calculated based on IPCC (2006) See Equation 2.2

Dinitrogen monoxide, emission to air/low population density	Elementary Flow	Direct N_2O: inputs are from producer surveys and calculated based on IPCC (2006) See Equation 1
Dinitrogen monoxide, emission to air/low population density	Elementary Flow	Indirect N_2O from volatilization: inputs are from producer surveys and calculated based on IPCC (2006) See Equation 2
Dinitrogen monoxide, emission to air/low population density	Elementary Flow	Indirect N_2O from leaching: inputs are from producer surveys and calculated based on IPCC (2006). See Equation 3
Nitrate, emission to air, low population density	Elementary Flow	Inputs are from producer surveys and calculated based on IPCC (2006). See Equation 3.1
Nitrogen oxides (emissions to air/low population density)	Elementary Flow	Inputs are from producer surveys and calculated based on IPCC (2006). See Equation 2.1
Phosphate, emission to water/groundwater	Elementary Flow	Inputs are from producer surveys and calculated based on SALCA-P (Prasuhn, 2006). See Equation 4
Phosphate, emission to water/surface water	Elementary Flow	Inputs are from producer surveys and calculated based on SALCA-P (Prasuhn, 2006). See Equation 5

Appendix H

Table H-1 Background processes and inputs to openLCA for the N fraction component of manure modelling. Inputs are from the IFA Report (2022).

Process Modelled	**Provider**
Ammonia, anhydrous, liquid	Ammonia production, partial oxidation, liquid | ammonia, anhydrous, liquid | APOS, U - ROW
Ammonium nitrate	Ammonium nitrate production | ammonium nitrate | APOS, U - ROW
Ammonium sulfate	Ammonium sulfate production | ammonium sulfate | APOS, U - ROW
Calcium ammonium nitrate	Calcium ammonium nitrate production | calcium ammonium nitrate | APOS, U - ROW
Urea	Urea production | urea | APOS, U - ROW

Table H-2 Background processes and inputs to openLCA for the P fraction component of manure modelling. Inputs are from the IDA Report (2022).

Process Modelled	**Provider**
Single superphosphate	Single superphosphate production | single superphosphate | APOS, U - ROW
Triple superphosphate	Triple superphosphate production | triple superphosphate | APOS, U - ROW

Table H-3 Background processes and inputs to openLCA for the K fraction component of manure modelling. Inputs are from the IFA Report (2022).

Process Modelled	**Provider**
Potassium chloride	Potassium chloride production | potassium chloride | APOS, U - ROW
Potassium sulfate	Potassium sulfate production | potassium sulfate | APOS, U - ROW

Appendix I

Table I-1 Background processes and inputs to openLCA for the alfalfa component of modelling

Process Modelled	Provider
Occupation, annual crop, organic	Elementary Flow
Pea seed, organic, for sowing[1]	Pea seed production, organic, for sowing | pea seed, organic, for sowing | APOS, U - ROW
Tillage, ploughing	Tillage, ploughing | tillage, ploughing | APOS, S - CA-QC
Sowing	Sowing | sowing | APOS, S - CA-QC

[1] Proxy for alfalfa seed

Table I-2 Background processes and inputs to OpenLCA for the lentils component of modelling

Process Modelled	Provider
Lentil seed, for sowing	Lentil seed production, for sowing | lentil seed, for sowing |APOS, U - GLO
Occupation, annual crop, organic	Elementary Flow
Sowing	Sowing | sowing | APOS, S - CA-QC
Tillage, harrowing, by offset disc harrow	Tillage, harrowing, by offset disc harrow | tillage, harrowing, by offset disc harrow | APOS, S - CA

Table I-3 Background processes and inputs to openLCA for the pea component of modelling

Process Modelled	Provider
Occupation, annual crop, organic	Elementary Flow
Pea seed, organic, for sowing	Pea seed production, organic, for sowing | pea seed, organic, for sowing | APOS, U - ROW

Tillage, ploughing	Tillage, ploughing | tillage, ploughing | APOS, S - CA-QC
Sowing	Sowing | sowing | APOS, S - CA-QC

Table I-4 Background processes and inputs to OpenLCA for the red/yellow clover component of modelling

Process Modelled	**Provider**
Clover seed, Swiss integrated production, for sowing[1]	Clover seed production, Swiss integrated production, for sowing | clover seed, Swiss integrated production, for sowing | APOS, U - CH
Occupation, annual crop, organic	Elementary Flow
Tillage, ploughing	Tillage, ploughing | tillage, ploughing | APOS, S - CA-QC
Sowing	Sowing | sowing | APOS, S - CA-QC

[1] Proxy for organic clover seed.

Appendix J

Table J-1 Background processes and inputs to openLCA for the cover crop component of modelling

Process Modelled	**Provider**
Rye	Refer to Table N-2
Tillage, harrowing, by offset disc harrow	Tillage, harrowing, by offset disc harrow | tillage harrowing, by offset disc harrow | APOS, S - CA
Tillage, ploughing	Tillage, ploughing | tillage, ploughing |APOS, S - CA-QC
Tillage, rolling	Tillage, rolling | tillage, rolling | APOS, S - CA-QC

Table J-2 Background processes and inputs to openLCA for the rye component of modelling

Process Modelled	**Provider**
Fertilising, by broadcaster	Fertilising, by broadcaster | fertilising by broadcaster | APOS, S - CA-QC
Occupation, annual crop, organic	Elementary Flow
N Fraction Manure	Refer to Table L-1
P Fraction Manure	Refer to Table L-2
K Fraction Manure	Refer to Table L-3
Rye seed, organic, for sowing	Rye seed production, organic, for sowing | rye seed, organic, for sowing | APOS, U - ROW
Sowing	Sowing | sowing | APOS, S - CA-QC
Tillage, cultivating, chiselling	Tillage, cultivating, chiselling | tillage, cultivating, chiselling | APOS, S - CA-QC

Appendix K

Table K-1 Background processes and inputs to openLCA for the mineral amendments component of modelling

Process Modelled	**Provider**
Calcium carbonate, precipitated[1]	Calcium carbonate production, precipitated | calcium carbonate, precipitated | APOS, U - ROW
Compost	Treatment of biowaste, industrial composting | compost | APOS, U - ROW
Fishmeal, 63-65% protein	Fishmeal and fish oil production, 63-65% protein, from fish residues | fishmeal, 63-65% protein | APOS, U - ROW
Gypsum, mineral	Magnesium sulfate production | magnesium sulfate | APOS, S - ROW
Magnesium sulfate[2]	Magnesium sulfate production | magnesium sulfate | APOS, S - ROW
Molybdenite[3]	Copper mine operation and benediction, sulfide ore | molybdenite | APOS, S - CA
Phosphate rock, beneficiated	Phosphate rock beneficiation | phosphate rock beneficiated | APOS, U - ROW
Potash salt[4]	Potash salt production | potash salt | APOS, S - ROW
Potassium sulfate	Potassium sulfate production | potassium sulfate | APOS, S - ROW
Rock crushing[5]	Rock crushing | rock crushing | APOS, S - ROW
Sodium borates[6]	Sodium borates production | sodium borates | APOS, S - ROW
Sodium tetrahydridoborate[7]	Brown-Schlesinger process | sodium tetrahydridobrate | APOS, S - GLO
Sulfur	Natural gas production | sulfur | APOS, S - CA-AB

Zinc monosulfate	Primary zinc production from concentrate | zinc monosulfate | APOS, S - ROW
Transport, freight, lorry 7.5-16 metric ton, EURO6[8]	Transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - ROW

[1] Proxy for GSR Dormant Calcium

[2] Proxy for Sulpomag and K Mag

[3] Proxy for Rebound Molybdenum

[4] Proxy for Teckmac (in addition for use as Potash Salt)

[5] Proxy for Azomite

[6] Proxy for Ulexite and Solubor

[7] Proxy for Boron

[8] Inputs are from Nagy and colleagues (1999) Toma and Bouma Management Consultants (2006)

Appendix L

Table L-1 Average Canadian fertilizer consumption from 1961-2019 by N contributions, P_2O_5 contributions, and K_2O contributions (IFA, 2022)

Canadian Fertilizer Consumption Average 1961-2019 (IFA)		
Product	**Consumption (metric tonnes)**	**% of Total**
Ammonia direct application (N)	18478.2	38%
Ammonium nitrate (N)	3902.3	7%
Ammonium sulphate (N)	3386.1	6%
Calcium ammonium nitrate (N)	371.1	1%
Urea (N)	30721.2	54%
Total N	56858.9	100%
Single superphosphate (P_2O_5)	69.8	11%
Triple superphosphate (P_2O_5)	577.4	89%
Total P_2O_5	647.2	100%
Potassium chloride (K_2O)	14888.4	98%
Potassium sulphate (K_2O)	323.8	2%
Total K_2O	15212.2	100%

Appendix M

Table M-1 Crop inventory data for Ontario farm #1 including functional unit conversions. Highlighted in yellow is the rye inventory data, which informs these calculations.

Crop	**Year Grown**	**Seeding Area (ha)**	**Seeding Area (ha per t crop harvested)**	**Yield (t ha^{-1})**
Red Clover	2017	12.14	N/A	N/A
*Winter Wheat	2017	12.14	0.20	4.94
Soy	2018	20.23	0.45	2.22
Corn	2019	1.21	0.034	10.38
*Rye	2020	12.14	0.27	3.71

* Full inventory data provided

Table M-2 Nutrient application information specific to Rye

Crop	**Fertilizer type/Product**	**Application Rate (t ha^{-1})**	**Application Rate (t product per t of crop harvested)**	**Average N of fertilizer (%)**	**N% Source**
Rye	TekMac G&G	0.17	0.045	5.5	Tek Mac Enterprises, Wellesley, ON

	Pullet Manure (Conventional)	7.41	2	2	Provided by ON Farm 1

*The above values are used to calculate the F_{ON}

The following equations will draw upon data provided for Rye.

2.2.3.1 Annual Direct N_2O-N Emissions

The equation (Equation 1) for annual direct N_2O emissions for organically managed soils is as follows:

$$\textit{Equation 1)}\ N_2O\text{-}N = (F_{on} \times EF_1F_{on}) + (F_{cr} \times EF_2F_{cr}) + (F_{som} \times EF_1F_{som})$$

Where

- N_2O-N = annual direct N_2O-N emissions from N inputs to managed soils (kg N_2O-N yr^{-1})
    - Note: this value is in units of kg N_2O as N yr^{-1}. To convert this unit to kg N_2O yr^{-1}, the final solution of Equation 1 is multiplied by the molecular mass ratio of N_2O to N of (44/28 kg N_2O kg^{-1} N_2O-N)
- F_{on} = annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1}) (Equation 1.7)
- F_{cr} = annual amount of N in crop residues (above-ground and below ground), returned to soils (kg N yr^{-1}) (Equation 1.7)
- F_{som} = the net annual amount of N mineralized in mineral soils as a result of loss of soil carbon through change in land use or management (kg N yr^{-1}) (Equation 1.8)
- EF_1F_{on} = emissions factor for organic nitrogen lost as N_2O following application to agricultural soils (kg N_2O-N)
- EF_2 F_{cr} = emissions factor for crop residue nitrogen lost as N_2O following application to agricultural soils (kg N_2O-N)
- EF_1 F_{som} = emission factor for N additions from mineral fertilizers, organic amendments and crop residues, and N mineralized from mineral soil as a result of loss of soil carbon (kg N_2O-N)

EXAMPLE:

ON_1a: Rye

$$N_2O\text{-}N = [(51.81 \text{ kg N y}^{-1} \times 0.017 \text{ kg } N_2O\text{-}N \text{ kg}^{-1} \text{ N applied}) + (4.40 \text{ kg N y}^{-1} \times 0.017 \text{ kg } N_2O\text{-}N \text{ kg}^{-1} \text{ N applied}) + (25.88 \text{ kg N y}^{-1} \times 0.017 \text{ kg } N_2O\text{-}N \text{ kg}^{-1} \text{ N applied})]$$

$$\text{Total } N_2O\text{-}N = 1.31 \text{ kg } N_2O\text{-}N$$

$$\text{Total direct } N_2O = 1.31 \text{ kg } N_2O\text{-}N \text{ yr}^{-1} \times (44 \div 28 \text{ kg } N_2O \text{ kg}^{-1} N_2O\text{-}N)$$

$$\text{Total direct } N_2O = 2.045 \text{ kg } N_2O \text{ yr}^{-1} \text{ per t crop harvested}$$

The F_{on} values were calculated by summing the nutrients (where applicable) applied to a crop, multiplied by the nitrogen (N) content of the nutrient application (Equation 1.1).

$$\text{Equation 1.1) } F_{Amendments} = [(A_1 \times N_{Amendmens1}) + (A_2 \times N_{Amendment2}) \ldots + (A_X \times N_{AmendmentX})]$$

Where:

- $F_{amendments}$ = total nitrogen content of manures and organic amendments applied (kg N t^{-1})
- A_1 = amount of first manure or organic amendment applied to crop (kg N t^{-1})
- $N_{Amendment1}$ = nitrogen content of amendment 1 (%)
- A_2 = amount of second manure or organic amendment applied to crop (kg N t^{-1})
- $N_{Amendment2}$ = nitrogen content of amendment 2 (%)
- A_x = additional amount of manures or organic amendments applied to crop (kg N t^{-1})
- $N_{AmendmentX}$ = nitrogen content of additional amendments applied to crop (%)

EXAMPLE:

ON_1a: Rye

$$F_{Amendments} = [(0.04535 \text{ kg N t}^{-1} \times 0.055) + (2 \text{ kg N t}^{-1} \times 0.02)]$$

$$F_{Amendments} = 42.49 \text{ kg N per t harvested crop}$$

In addition to manures and organic nutrient applications, green manures and residual nitrogen content from nitrogen fixing crops in a rotation were included in the F_{on} value. Green manure nitrogen content was calculated based on the following Equation 1.2:

$$\textit{Equation 1.2)}\ F_{NitrogenGM} = [(DM_G \times N_G) + (DM_{AGR} \times N_{AGR}) + (DM_{BGR} \times N_{BGR})] \times (Y \div 1000)$$

Where

- $F_{NitrogenGM}$ = kilograms of nitrogen per hectare from green manures and cover crops that will be divided between subsequent crops in a crop rotation using Equation 1.3 (kg N ha^{-1})
- Y = yield (if applicable) (kg N ha^{-1})
- DM_G = typical grain dry matter fraction (%) (CCOF, 2015; Feedipedia, 2022)
- N_G = nitrogen content of the grain partitioning of the crop (g N kg^{-1})
- N_{AGR} = nitrogen content of the aboveground residue partitioning of the crop (g N kg^{-1})
- N_{BGR} = nitrogen content of the belowground residue partitioning of the crop (g N kg^{-1})
- G_{DM} = calculated plant partitioning of total plant dry matter into grain (% of DM)
- AGR_{DM} = calculated plant partition of total plant dry matter into aboveground residue (% of DM)
- BGR_{DM} = calculated plant partition of total plant dry matter into belowground residue (% DM)

EXAMPLE:

ON_1a: Rye

Not applicable to rye

Since some leguminous crops were harvested, the nitrogen available to subsequent crops did not include the grain portion of the plant. Therefore, to find the nitrogen content of leguminous crops with a yield, Equation 1.2.1 was used:

$$\textit{Equation 1.2.1)}\ F_{NitrogenL} = [(DM_{AGR} \times N_{AGR}) + (DM_{BGR} \times N_{BGR})] \times (Y \div 1000)$$

Where

- $F_{NitrogenL}$ = kilograms of nitrogen per hectare from leguminous crops with a harvest that will be divided between subsequent crops in a crop rotation using Equation 1.3.1 (kg N ha^{-1})
- All other variable are the same as in Equation 1.2

EXAMPLE:

ON_1a: Rye

Not applicable for rye

From the nitrogen content of green manures and cover crops, the fraction of N inputs and upstream environmental impacts that are allocated to the subsequent crop can be determined with Equation 1.3:

$$\textit{Equation 1.3)}\ F_{NFractionGM} = N_{crop1} \div [N_{crop1} + N_{crop2} + \dots N_{cropX}]$$

Where

- $F_{NFractionGM}$ = the fraction of nitrogen inputs and emissions from prior green manures or cover crops grown (%)
- N_{crop1} = total nitrogen content of green manure (t N ha^{-1})
- N_{crop2} = the total nitrogen content of the crop after the green manure in rotation (t N ha^{-1})
- N_{cropX} = nitrogen content of last crop in rotation before another green manure (t N ha^{-1})

EXAMPLE:

ON_1a: Soybean contribution to Rye

Table M-3 Dry matter plant partitioning and nitrogen concentrations by plant partition for corn and rye

Crop	**Grain DM (%)**	**AGR DM (%)**	**BGR DM (%)**	**DM_G (%)**	**Grain N conc (g N kg^{-1} grain)**	**AGR N conc (g N kg^{-1})**	**BGR N conc (g N kg^{-1})**	**Source**
Corn	35	46	20	86.3	12.72	9.37	7.55	Thiagarajan et al. (2018)
Rye	39	48	17	86.8	20.79	8.81	12.39	Thiagarajan et al. (2018)

$$\text{Corn Nitrogen} = [(0.35 \times 12.72 \text{ g N kg}^{-1}) + (0.46 \times 9.37 \text{ g N kg}^{-1}) + (0.2 \times 7.55 \text{ g N kg}^{-1})]$$

$$\text{Corn Nitrogen} = (4.452 \text{ g N kg}^{-1} + 4.3102 \text{ g N kg}^{-1} + 1.51 \text{ g N kg}^{-1})$$

$$\text{Corn Nitrogen} = 10.2722 \text{ g N kg}^{-1}$$

$$\text{Corn Nitrogen per FU} = [(10.2722 \text{ g N kg}^{-1} \times 10.38 \text{ t ha}^{-1}) \div 1000]$$

$$\text{Corn Nitrogen per FU} = 0.1066 \text{ t N ha}^{-1} \text{ harvested crop}$$

$$\text{Rye Nitrogen} = [(0.39 \times 20.79 \text{ g N kg}^{-1}) + (0.48 \times 8.81 \text{ g N kg}^{-1}) + (0.17 \times 12.39 \text{ g N kg}^{-1})]$$

$$\text{Rye Nitrogen} = (7.4844 \text{ g N kg}^{-1} + 4.2288 \text{ g N kg}^{-1} + 2.1063 \text{ g N kg}^{-1})$$

$$\text{Rye Nitrogen} = 13.8195 \text{ g N kg}^{-1}$$

$$\text{Rye Nitrogen per FU} = [(13.8195 \text{ g N kg}^{-1} \times 3.71 \text{ t ha}^{-1}) \div 1000]$$

$$\text{Rye Nitrogen per FU} = 0.05122 \text{ t N ha}^{-1} \text{ harvested crop}$$

$$F_{NFractionGM} = 0.1066 \text{ t N} \div (0.1066 \text{ t N} + 0.05122 \text{ t N})$$

$F_{NFractionGM}$ = 67.55% of available soy impacts are allocated to corn

$F_{NFractionGM}$ = 0.05122 t N ÷(0.1066 t N + 0.05122 t N)

$F_{NFractionGM}$ = 32.45 % of available soy impacts are allocated to rye

Due to the harvesting of the grain portion of leguminous crops, the fraction of N inputs and emissions from leguminous crops with a harvest is found using Equation 1.3.1:

$$\text{Equation 1.3.1)}\ F_{NFractionL} = N_{crop1} \div [N_{crop1} + N_{crop2} + \ldots N_{cropX}]$$

Where

- $F_{NFractionL}$ = the fraction of nitrogen inputs and emissions from prior leguminous crop grown (%)
- N_{crop1} = total nitrogen content of the crop grown immediately after the leguminous crop with a harvest (t N ha^{-1})
- N_{crop2} = the total nitrogen content of the crop grown next in the rotation (t N ha^{-1})
- N_{cropX} = nitrogen content of last crop in rotation before another leguminous crop (t N ha^{-1})

EXAMPLE:

ON_1a: Rye

Not applicable to rye

The outputs of Equation 1.3.1 for one rotation will sum to 100%, similarly to Equation 1.3.

To determine the amount of nitrogen that is available from the green manures to be allocated to subsequent crops, Equation 1.4 is used:

$$\text{Equation 1.4)}\ Nitrogen_{GM} = 2000 \times (N_G \div 1000)] + [(2000 \div G_{DM}) \times AGR_{DM} \times (N_{AGR} \div 1000)] + [(2000 \div G_{DM}) \times BGR_{DM} \times (N_{BGR} \div 1000)]$$

Where

- Nitrogen_{GM} = total nitrogen available from the green manures to be allocated (kg N ha^{-1})
- 2000 = assumed dry matter grain yield of 2 t ha^{-1} (Thiagarajan et al., 2018)
- DM_G = typical grain dry matter fraction (%) (CCOF, 2015; Feedipedia, 2022)
- N_G = nitrogen content of the grain partitioning of the crop (g N kg^{-1})
- N_{AGR} = nitrogen content of the aboveground residue partitioning of the crop (g N kg^{-1})
- N_{BGR} = nitrogen content of the belowground residue partitioning of the crop (g N kg^{-1})
- G_{DM} = calculated plant partitioning of total plant dry matter into grain (% of DM)
- AGR_{DM} = calculated plant partition of total plant dry matter into aboveground residue (% of DM)
- BGR_{DM} = calculated plant partition of total plant dry matter into belowground residue (% DM)

EXAMPLE:

ON_1a: Rye

Not applicable to rye

Leguminous crops with a harvest are treated slightly differently from green manures with no harvest. Determining available nitrogen that can be allocated to subsequent crops is done using Equation 1.4.1:

$$\text{Equation 1.4.1) } Nitrogen_L = [(AGR_{DM} \div G_{DM}) \times (N_{AGR} \div 1000) \times DM_G \times Y] + [(BGR_{DM} \div G_{DM}) \times (N_{BGR} \div 1000) \times DM \times Y]$$

Where

- Nitrogen_L = total nitrogen available from the leguminous crops with a harvest to be allocated (kg N ha^{-1})
- Y= yield of leguminous crop with a harvest (kg ha^{-1})
- DM_G = typical grain dry matter fraction (%) (CCOF, 2015; Feedipedia, 2022)
- N_{AGR} = nitrogen content of the aboveground residue partitioning of the crop (g N kg^{-1})
- N_{BGR} = nitrogen content of the belowground residue partitioning of the crop (g N kg^{-1})
- G_{DM} = calculated plant partitioning of total plant dry matter into grain (% of DM)

- AGR_{DM} = calculated plant partition of total plant dry matter into aboveground residue (% of DM)
- BGR_{DM} = calculated plant partition of total plant dry matter into belowground residue (% DM)

EXAMPLE:

ON_1a: Rye

This equation is modified for soy, see Figure 17.

Table M-4 Dry matter plant partitioning and nitrogen concentrations by plant partition for soy

Crop	**Grain DM (%)**	**AGR DM (%)**	**BGR DM (%)**	**DM_G (%)**	**Grain N conc (g N kg^{-1} grain)**	**AGR N conc (g N kg^{-1})**	**BGR N conc (g N kg^{-1})**	**Source**
Soy	0.33	0.5	0.18	.87	62.51	6.6	10	Thiagarajan et al. (2018)

$$F_{NitrogenL} = [(0.5 \div 0.33) \times (6.6 \text{ g N kg}^{-1} \div 1000) \times 2223.945 \text{ kg ha}^{-1} \times 0.87] + [(0.18 \div 0.33) \times (10 \text{ g N kg}^{-1} \div 1000) \times 2223.945 \text{ kg ha}^{-1} \times 0.87]$$

$F_{NitrogenL}$ = 29.9 kg N ha^{-1} available from soy to allocate to the subsequent crops in the rotation

The resulting percentage of the $Nitrogen_{GM}$ or $Nitrogen_{L}$ equation (Equation 1.4 or Equation 1.4.1) is then multiplied by the results of Equation 1.3 (or Equation 1.3.1) to get a total kg N ha^{-1} of green manure or leguminous crop that is contributing to the subsequent crop in the rotation. This operation is shown below in Equation 1.5:

Equation 1.5) $F_{TotalGM} = F_{NitrogenGM} \times Nitrogen_{GM}$

or

$$F_{TotalL} = F_{NitrogenL} \times Nitrogen_{L}$$

Where

- $F_{TotalGM}$ = total nitrogen from green manure allocated to the subsequent crop in rotation on a land area basis (kg N ha^{-1})
- $Nitrogen_{GM}$ = total nitrogen available from the green manures to be allocated (kg N ha^{-1})
- $F_{NFractionGM}$ = the fraction of nitrogen inputs and emissions from prior green manures or cover crops grown (%)

And

- F_{TotalL} = total nitrogen from leguminous crop with a harvest allocated to the subsequent crop in rotation on a land area basis (kg N ha^{-1})
- $Nitrogen_{L}$ = total nitrogen available from the leguminous crops with a harvest to be allocated (kg N ha^{-1})
- $F_{NFractionL}$ = the fraction of nitrogen inputs and emissions from prior leguminous crop grown (%)

EXAMPLE:

ON_1a: Rye

$$F_{TotalL} = 29.9 \text{ kg N ha}^{-1} \times 32.45\ \%$$

$$F_{TotalL} = 9.7 \text{ kg N ha}^{-1} \text{ allocated to rye}$$

To convert the nitrogen contributions from kg ha^{-1} to a functional unit basis (kg t^{-1} harvested crop), solutions from Equations 1.5 are substituted into Equation 1.6:

$$Equation\ 1.6)\ F_{TotalFU} = F_{Total} \div (Y \div 1000)$$

Where

- $F_{TotalFU}$ = fraction of nitrogen from leguminous crop or green manure allocated to the subsequent crop in rotation on a functional unit basis (kg N t^{-1})

- F_{Total} = fraction of nitrogen from leguminous crop or green manure allocated to the subsequent crop in rotation on a land area basis (kg N ha^{-1})
- Y = yield of the subsequent crop in rotation (kg ha^{-1})

EXAMPLE:

ON_1a: Rye

$$F_{TotalFU} = 9.7 \text{ kg N ha}^{-1} \div (3706.6 \text{ kg ha}^{-1} \div 1000)$$

$$F_{TotalFU} = 2.62 \text{ kg N t}^{-1} \text{ per harvested crop}$$

The resulting values of Equation 1.6, in addition to the nitrogen fraction from organic amendments (Equation 1.1), are added together and result in F_{on}: the variable from Equation 1. This operation is shown with Equation 1.7 below:

$$\text{Equation 1.7)}\ F_{on} = F_{TotalFU} + F_{Amemdment}$$

Where

- F_{on} = annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1})
- $F_{TotalFU}$ = fraction of nitrogen from leguminous crop or green manure allocated to the subsequent crop in rotation on a functional unit basis (kg N t^{-1})
- $F_{Amendments}$ = total nitrogen content of manures and organic amendments applied (kg N t^{-1})

EXAMPLE:

ON_1a: Rye

$$F_{on} = 9.32 \text{ kg N yr}^{-1} + 42.49 \text{ kg N t}^{-1}$$

$$F_{on} = 51.81 \text{ kg N yr}^{-1} \text{ per t harvested crop}$$

In the case of a green manure that is grown on the same field at the same time as a crop, this is treated as a rotation with the green manure being grown first. The same allocation calculations apply. Since cover crops are primarily planted for soil health, erosion mitigation, and weed control (Clark, 2008; Dabney et al., 2001; Kaspar and Singer, 2011; Reeves, 1994) rather than fixing nitrogen, the environmental impacts of cover crops grown in conjunction with another crop are placed solely on that one crop. Similarly, nitrogen impacts of manure and other nutrient applications land only on the proceeding crop. This is because it is assumed producers are practicing precision nutrient management, and therefore only applying the necessary manure, nutrients, and subsequent nitrogen to support the crop to which it is directly applied (Agriculture and Agri-Food Canada, 2022b; Ess et al., 2001; Hedley, 2015; Patil, 2009).

F_{cr} values used in Equation 1 were determined using Equation 1.7:

$$\textit{Equation 1.8)}\ F_{cr} = [(BGR_{\%\ of\ DM} \div G_{\%\ of\ DM}) \times N_{BGR} \times DM_{crop}] + [(AGR_{\%\ of\ DM} \div G_{\%\ of\ DM}) \times N_{AGR} \times DM_{crop}]$$

Where

- F_{cr} = annual amount of N in crop residues (above-ground and below ground), returned to soils (kg N yr^{-1})
- $BGR_{\%\ of\ DM}$ = partitioning of total plant dry matter (DM) into belowground residue for entire crop rooting depth (Thiagarajan et al., 2018, Table 3)
- $G_{\%\ of\ DM}$ = plant partitioning of total plant dry matter into grain (Thiagarajan et al., 2018, Table 3)
- N_{BGR} = N concentration of belowground residue (g N kg^{-1}) (Thiagarajan et al., 2018 Table 2)
- DM_{crop} = dry matter of crop residues at harvest (%), from nutritional tables in Feedipedia (Feedipedia, 2020) (dry matter, aerial (fresh) from Feedipdia used as most accurate harvest dry matters)
- $AGR_{\%\ of\ DM}$ = partitioning of total plant dry matter into aboveground residue (Thiagarajan et al., 2018, Table 3)
- N_{AGR} = N concentration of aboveground residue (g N kg^{-1}) (Thiagarajan et al., 2018, Table 2)

ON_1a: Rye

Table M-5 . Percent dry matter concentrations for plant partitions, nitrogen content for plant partitions, and total crop dry matter concentration for rye

Crop	**BGR$_{\%}$** **of DM** **(%)**	**G$_{\%}$** **of DM** **(%)**	**AGR$_{\%}$** **of DM** **(%)**	**N$_{BGR}$** (g N/kg BGR)	**N$_{AGR}$** (g N/kg BGR)	**Source**	**DM$_{crop}$** **(%)**	**Source**
Rye	17	36	48	12.39	8.81	Thiagarajan et al., 2018	0.25 (25% dry matter, 75% moisture)	Feedipedia (2022)

$$F_{cr} = [(0.17 \div 0.36) \times 12.39 \text{ g N kg}^{-1} \times 0.25] + [\,(0.48 \div 0.36) \times 8.81 \text{ g N kg}^{-1} \times 0.25]$$

$$F_{cr} = 4.40 \text{ kg N yr}^{-1} \text{ per t crop harvested}$$

F_{som} values used in Equation 1 were found using the IPCC 2006, Ch. 11 equation 11.8: N mineralized in mineral soils as a result of loss of soil C through change in land use or management, here known as Equation 1.8:

Equation 1.9) $F_{som} = LU[(\Delta C_{mineral,\,LU}\ (1 \div R)) \times 1000]$

Where

- F_{som} = the net annual amount of N mineralized in mineral soils as a result of loss of soil carbon through change in land use or management (kg N)
- $C_{mineral,\,LU}$ = average annual loss of soil carbon for each land management practice (Mg C)
- R = C:N ratio of the soil organic matter
- LU = land-use and/or management system type

Table M-6 Average delta SOC computed in Holos and allocated among crops grown on the farm based on the functional unit.

Crop	**Average Change in SOC (kg C ha-1)**	**Seeding Area (per FU)**	**ΔSOC (per FU, kg C/t)**
Rye	1055.01	0.27	284.63
Winter Wheat		0.20	214.47

EXAMPLE:

ON_1a: Rye

F_{som} = (284.63 kg CO2 t^{-1} × (1 ÷11)) (the multiplication by 1000 did not apply since our units cancelled it out)

F_{som} = 25.88 kg N yr^{-1} per t crop harvested

In this analysis, the C:N ratio of the soil organic matter (R) is 11 for all soil types. This value comes from the National Inventory Report (NIR), part 2 (2022) stating that "A database containing soil organic carbon (SOC) and N for all major soils in Saskatchewan (a data set of about 600) was used to derive an average C:N ratio of 11 with a standard deviation of 1.9. The C:N ratio of agricultural soils is considered to be consistent among regions" (p. 133). Furthermore, this value of 11 falls within the IPCC 2006 C:N ratio guidelines, which propose a C:N ratio range from 8-15. Values for $\Delta C_{mineral, LU}$ were taken directly from the Holos soil organic carbon modelling.

2.2.3.2 Annual Indirect N_2O-N Emissions

The IPCC's NIR identifies indirect t N_2O emissions from volatilization as those emissions "from atmospheric deposition of N volatilized from managed soils" (IPCC, 2006, p. 21). The indirect N_2O volatilization equation for organically managed soils is the following:

Equation 2) $N_2O_{[ATD]}\text{-}N = (F_{on} \times Frac_{gasm}) \times EF_4$

Where

- $N_2O_{[ATD]}$-N = annual amount of N_2O-N produced from atmospheric deposition of N volatilized from organically managed soils (kg N_2O-N yr^{-1})
    - Note: this value is in units of kg $N_2O_{[ATD]}$ as N yr^{-1}. To convert this unit to kg N_2O yr^{-1}, the final solution of Equation 2 is multiplied by the molecular mass ratio of N_2O to N of (44/28 kg N_2O kg^{-1} N_2O-N)
- F_{on} = annual amount of managed animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1})
- $Frac_{gasm}$ = fraction of applied organic N fertilizer materials (F_{on}) that volatilizes as NH_3 and NO_x [kg N volatilized (kg of N applied of deposited)$^{-1}$]
- EF_4 = emissions factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces [kg N_2O-N (kg NH_3-N + NO_x-N volatilized)$^{-1}$]

EXAMPLE:

ON_1a: Rye

$N_2O_{(ATD)}$-N = [(51.81 kg N yr^{-1} × 0.237 kg NH_3-N volatilized kg^{-1} N applied) × 0.0043 kg N-N_2O [kg NH_3-N + NOx-N volitzlaized^{-1}]]

$N_2O_{(ATD)}$-N = 0.047 kg $N_2O_{(ATD)}$-N yr^{-1} per t crop harvested

Total $N_2O_{(ATD)}$ = 0.047 kg $N_2O_{(ATD)}$-N (44 ÷ 28 kg N_2O yr^{-1}/kg $N_2O_{(ATD)}$-N)

Total $N_2O_{(ATD)}$ = 0.081 kg N_2O yr^{-1} per t crop harvested

Equations for NO_x produced and NH_3 produced are found using Equations 2.1 and 2.2 respectively.

Equation 2.1) $NO_x \text{ produced} = (F_{on} \times Frac_{gasm}) \times 0.1 \times (46 \div 14)$

Where

- NO_x produced = annual amount of nitrogen oxide emissions to air (kg NO_x)
- F_{on} = annual amount of managed animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1})
- $Frac_{gasm}$ = fraction of applied organic N fertilizer materials (F_{on}) that volatilizes as NH_3 and NO_x [kg N volatilized (kg of N applied of deposited)$^{-1}$]
- 0.1 = Proportion of N volatilized as NO_x (Brentrup et al., 2000)
- (46 ÷ 14) = molecular weight conversion for NO_x-N to NO_2 (US EPA, 2021)
    - Note: although NO_x refers to both nitrogen oxide (NO) and nitrogen dioxide (NO_2), the US EPA (2021) recommends using the molecular weight conversion for NO_2 due to the "fast rate of transformation of NO to NO_2 under ambient conditions".

EXAMPLE:

ON_1a: Rye

$$NO_x\text{-N} = [(51.81 \text{ kg N yr}^{-1} \times 0.237 \text{ kg } NH_3\text{-N volatilized kg}^{-1} \text{ N applied}) \times 0.1]$$

$$NOx\text{-N} = 1.11 \text{ kg } NO_x\text{-N}$$

$$\text{Total } NO_x = 1.11 \text{ kg } NO_x\text{-N} \times (46 \div 28 \text{ kg } NO_x \text{ kg}^{-1} \text{ } NO_x\text{-N})$$

$$\text{Total } NO_x = 1.83 \text{ kg } NO_x \text{ yr}^{-1} \text{ per t crop harvested}$$

$$\textit{Equation 2.2) } NH_3 \textit{ produced} = (F_{on} \times Frac_{gasm}) \times 0.9 \times (17 \div 14)$$

Where

- NH_3 produced = annual amount of ammonia emissions to air (kg NH_3)
- F_{on} = annual among of managed animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1})
- $Frac_{gasm}$ = fraction of applied organic N fertilizer materials (F_{on}) that volatilizes as NH_3 and NO_x [kg N volatilized (kg of N applied of deposited)$^{-1}$]
- 0.9 = Proportion of N volatilized as NH_3 (Brentrup et al., 2000)
- (17 /14) = molecular weight conversion for NH_3-N to NH_3

EXAMPLE:

ON_1a: Rye

$$NH_3\text{-}N = [(51.81 \text{ kg N yr}^{-1} \times 0.237 \text{ kg } NH_3\text{-}N \text{ volatilized kg}^{-1} \text{ N applied}) \times 0.9]$$

$$\text{Total } NH_3 = 10.03 \text{ kg } NH_3\text{-}N \times (17 \div 28 \text{ kg } NH_3 \text{ kg}^{-1} \text{ } NH_3\text{-}N)$$

$$NH_3 = 6.087 \text{ kg } NH_3 \text{ yr}^{-1} \text{ per t crop harvested}$$

Indirect nitrogen emissions from leaching and runoff are calculated with Equation 3, detailed below:

$$\textit{Equation 3)}\ N_2O_{[L]}\text{-}N = (F_{on} + F_{cr} + F_{som}) \times \ Frac_{leach\text{-}[H]} \times EF_5$$

Where

- $N_2O_{[L]}$-N = annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs (kg N2O–N yr^{-1})
    - Note: this value is in units of kg $N_2O_{[L]}$ as N yr^{-1}. To convert this unit to kg N_2O yr^{-1}, the final solution of Equation 3 is multiplied by the molecular mass ratio of N_2O to N of (44/28 kg N_2O kg^{-1} N_2O-N)
- F_{on} = annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1}) (Equation 1.2)
- F_{cr} = annual amount of N in crop residues (above-ground and below ground), returned to soils (kg N yr^{-1}) (Equation 1.4)
- F_{som} = the net annual amount of N mineralized in mineral soils as a result of loss of soil carbon through a change in land use or management (kg N yr^{-1}) (Equation 1.5)
- $Frac_{leach\text{-}[H]}$ = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff (kg N)
- EF_5 = emission factor for N_2O emissions from N leaching and runoff (kg N_2O–N)

EXAMPLE:

ON_1a: Rye

$$N_2O_{[L]}\text{-}N = (51.81 \text{ kg N yr}^{-1} + 4.40 \text{ kg N yr}^{-1} + 25.88 \text{ kg N yr}^{-1}) \times 0.26 \text{ kg N kg}^{-1} \text{ of N additions} \times 0.0031 \text{ kg } N_2O \text{ kg}^{-1} \text{ N}$$

$$\text{Total } N_2O_{(L)} = 0.062 \text{ kg } N_2O_{[L]}\text{-N} \times (44 \div 28 \text{ kg } N_2O \text{ yr}^{-1} \text{ kg}^{-1} N_2O_{(ATD)}\text{-N})$$

$$\text{Total } N_2O_{(L)} = 0.097 \text{ kg } N_2O_{[L]} \text{ yr}^{-1} \text{ per t crop harvested}$$

To calculate the annual amount of nitrate runoff (NO_3^-) emissions, Equation 3.1, found below, is used:

$$\textit{Equation 3.1)}\ NO_3^- = [(F_{on} + F_{cr} + F_{som}) \times Frac_{leach\text{-}[H]}] \times (62 \div 14)$$

Where

- NO_3^- = annual amount of nitrate emissions by leaching (kg NO_3^-)
- F_{on} = annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N yr^{-1}) (Equation 1.2)
- F_{cr} = annual amount of N in crop residues (above-ground and below ground), returned to soils (kg N yr^{-1}) (Equation 1.4)
- F_{som} = the net annual amount of N mineralized in mineral soils as a result of loss of soil carbon through change in land use or management (kg N yr^{-1}) (Equation 1.5)
- $Frac_{leach\text{-}[H]}$ = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff (kg N)
- (62 /14) = molecular weight conversion for NO_3-N to NO_3

EXAMPLE:

ON_1a: Rye

$$NO_3^- = (51.81 \text{ kg N yr}^{-1} + 4.40 \text{ kg N yr}^{-1} + 25.88 \text{ kg N yr}^{-1}) \times 0.26 \text{ kg N kg}^{-1} \text{ of N additions} \times (62 \div 28 \text{ kg } NO_3^-/\ NO_3^-\text{-N})$$

$$NO_3^- = 44.49 \text{ kg } NO_3^- \text{ yr}^{-1} \text{ per t crop harvested}$$

2.2.3.3 Phosphorous Emissions to water

Developed by Agroscope, the SALCA-P emission models are used to estimate phosphorus emissions to water and are detailed in the Ecoinvent Tool Model Description (Faist Emmenegger et al., 2018). The following equation, Equation 4, accounts for phosphate leaching to groundwater:

Equation 4) $P_{gw} = P_{gwl} \times F_{gw}$

Where

- P_{gw} = quantity of P leached to ground water (kg P t^{-1})
- P_{gwl} = the average quantity of P leached to ground water for a land use category (kg P ha^{-1})
    - Note: a value of 0.07 kg P ha^{-1} is used in this study for arable land (Prasuhn, 2006)
- F_{gw} = correction factor for fertilization by slurry (dimensionless)
    - Note: a value of $(1+0.2/80\ P_{sl})$ is used for the correction factor where:
        - P_{sl} = quantity of P contained in the slurry or liquid sewage sludge (kg P ha^{-1})

EXAMPLE:

ON_1a: Rye

P_{gw} = 0.07 kg P ha^{-1} (no slurry was used, therefore no correction factor was required)

To get to kg P t^{-1} (i.e., per FU), P_{gw} must be divided by the rye yield:

$P_{gw} = 0.07 \text{ kg P ha}^{-1} \div 3.71 \text{ t ha}^{-1}$

P_{gw} = 0.0189 kg P per t crop harvested

To calculate the phosphate run-off to surface water, Equation 5 was used.

Equation 5) $P_{ro} = P_{rol} \times F_{ro}$

Where

- P_{ro} = quantity of P lost through run-off to rivers (kg P t^{-1})
- P_{rol} = the average quantity of P lost through run-off for a land use category (kg P ha^{-1})
    - Note: a value of 0.175 kg P ha^{-1} is used in this study for arable land (Prasuhn, 2006)

- F_{ro} = correction factor for fertilization with P (dimensionless)
  - Note: a value of $[(1+0.2/80\ \ P_{min}) + (0.7/80\ \ P_{sl}) + (0.4/80\ \ P_{man})]$ is used for the correction factor where:
    - P_{min} = quantity of P contained in mineral fertilizer (kg P ha^{-1})
    - P_{sl} = quantity of P contained in slurry or liquid sewage sludge (kg P ha^{-1})
    - P_{man} = quantity of P contained in solid manure (kg P ha^{-1})

EXAMPLE:

ON_1a: Rye

$$P_{ro} = 0.175 \text{ kg P ha}^{-1} \times [1 + (0.2 \div 80 \times 0.00272 \text{ kg } P_2O_5 \text{ t}^{-1}) + (0.4 \div 80 \times 0.04 \text{ kg } P_2O_5 \text{ t}^{-1})]$$

$$P_{ro} = 0.175 \text{ kg P ha}^{-1}$$

To get to kg P t^{-1} (i.e., per FU), P_{ro} must be divided by the rye yield:

$$P_{ro} = 0.175 \text{ kg P ha}^{-1} \div 3.71 \text{ t ha}^{-1}$$

$$P_{ro} = 0.0471 \text{ kg P per t crop harvested}$$

Appendix N

Table N-1 Sources for calculated plant partition of total plant dry matter (DM) into aboveground residue (AGR), belowground residues (BGR), and grain (G); and percent nitrogen of crop residues

Crop	**Grain DM**	**AGR DM**	**BGR DM**	**DM_G** (CCOF, 2015)	**Grain N concentration**	**AGR N concentration**	**BGR N concentration**	**Source(s)**
-	**%**	**%**	**%**	**%**	**g N/kg**	**g N/kg**	**g N/kg**	**-**
Red clover	0.4	0.1	0.5	88	24.6	13.8	18.17	Thiagarajan et al. (2018) Janzen et al. (2003)
Spelt	0.31	0.51	0.19	88	25.56	6.64	10.51	Thiagarajan et al. (2018)
Rye	0.34	0.51	0.15	89	18	6	10	Janzen et al. (2003)
Alfalfa	0.4	0.1	0.5	90.2	24.6	13.8	18.17	Thiagarajan et al. (2018) Janzen et al. (2003)
Oats	0.29	0.41	0.3	90.4	24.26	6.83	13.83	Thiagarajan et al. (2018)
Peas	0.25	0.57	0.18	89	37.36	21.02	21.99	Thiagarajan et al. (2018)
Soy	0.33	0.5	0.18	87	62.51	6.6	10	Thiagarajan et al. (2018)
Lentils	0.34	0.47	0.19	90.7	38.9	11.72	10	Thiagarajan et al. (2018)

Appendix O

Table O-1 Cradle-to-farm gate impact results for additional impact categories pertaining to organic production of wheat, corn, and soybeans in Ontario and Quebec.

	Wheat	Corn	Soybean
Freshwater Ecotoxicity (CTUe)	3.7E+06	1.1E+07	2.1E+06
Human Toxicity, Cancer (CTUh)	3.2E-05	2.2E-05	1.9E-05
Human Toxicity, Non-Cancer (CTUh)	1.9E-04	8.4E-05	4.3E-05
Ionizing Radiation (Bq C-14 eq)	1377.8	1817.6	763.6
Mineral Resource Use (kg deprived)	1.9	1.3	0.9
Ozone Layer Depletion (kg CFC-11 eq)	3.2E-05	1.7E-05	1.7E-05
Particulate Matter Formation (kg PM2.5 eq)	2.0	0.6	0.7
Photochemical Oxidant Formation (kg NMVOC eq)	6.8	2.4	9.4
Terrestrial Acidification (kg SO_2 eq)	3.0E-04	9.4E-05	8.5E-05

Appendix P

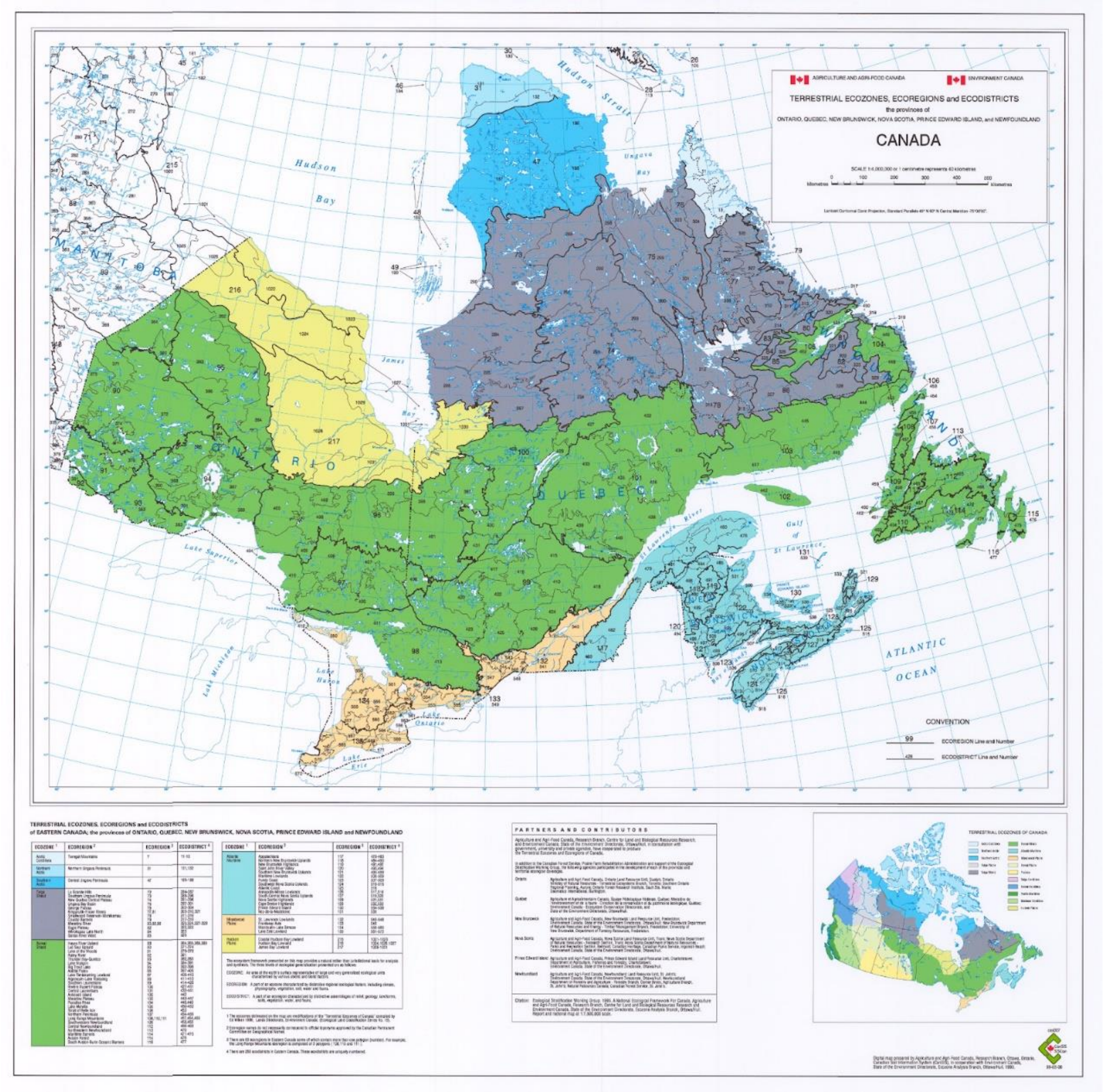


Figure P-1 Map of the terrestrial ecozones, ecoregions, and ecodistricts of Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland (Ecological Stratification Working Group, 1995)

Appendix Q

Table Q-1 Mineral amendment production locations and distances travelled from the production location to farms of use

Mineral Amendment	Production Location	Reference	Distance to Farm Use (ON)	Distance to Farm Use (QC)
calcium carbonite, precipitated (GSR Dormant Calcium)	Ontario	Lafarge (2022)	-	1, 137 km
Compost	On-site	–	-	-
Fishmeal, 63-65% protein, from fish residues	Regina, SK	Scoular (2022)	1, 353 km	-
Gypsum, Mineral	East Milford, Nova Scotia	Vagt (2015)	1, 755 km	1, 165 km
Magnesium Sulfate (SulpoMag)	Saskatchewan		1, 449 km	3, 000 km
Molybdenite (Rebound Molybdenum)	Prince Rupert, British Columbia	Bokovay et al. (2013)	2, 322 km	3, 970 km
Phosphate rock beneficiation (Soft Rock Phosphate)	Chicoutimi, QC	Arianne (2022)	785 km	-
Potash Salt (TekMac)	Wynyard, Saskatchewan	Cisyk (2019)	1, 449 km	3, 000 km
Potassium Sulfate	Wynyard, Saskatchewan		1, 449 km	3, 000 km
Rock Crushing (Azomite)	Utah, US	Boltz et al. (2021)	3, 405 km	3, 851 km
Sodium Borate (Ulexite & Solubor)	New Brunswick	Roulston & Waugh (1981)	1, 468 km	800 km
Sodium Tetrahydridoborate (Boron)	Manitoba		952 km	2, 098 km

Sulfur	Louisiana, US	Minerals Education Coalition (n.d.)	2, 317 km	2, 512 km
Zinc Sulfate	Ontario & Quebec	Natural Resources Canada (2016)	-	-

Appendix R

Table R-1 Cradle-to-harvest gate impact assessment data for CCLT (including and excluding average soil organic carbon change) (including all "Nutrient Application" contributions) expressed as kg CO_2 eq associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean in Eastern Canada (Ontario and Quebec)

Contributions	**Wheat**	**Corn**	**Soybeans**
Nitrous Oxide	766.7	234.1	216.2
Green Manure	56.4	2.3	16.1
Manure	41.8	22.1	16.3
Cover Crops	0.0	27.3	0.0
Mineral Amendments	0.0	13.6	0.5
Impacts from Leguminous Crops	7.7	5.8	0.0
Field Operations	88.1	50.5	68.8
Seed	31.9	2.5	15.5
SOC Change (kg CO_2)	-471.2	-156.8	-227.6
Total (excluding SOC)	992.5	358.2	333.4
Total (including SOC)	521.4	201.5	105.8

Appendix S

Table S-1 Cradle-to-harvest gate impact assessment data for Fossil and Nuclear Energy Deprivation (including all “Nutrient Application” contributions) expressed as MJ Deprived associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean in Eastern Canada (Ontario and Quebec)

Contribution	**Wheat**	**Corn**	**Soybean**
Green Manure	7.55E+02	32.4412	232.3316
Manure	6.52E+02	348.5358	253.4452
Cover Crop	0	341.2321	0
Mineral Amendment	0	290.4871	7.385451
Field Operations	1.23E+03	703.0496	960.9457
Seed Inputs	2.23E+02	19.29934	105.4152
Impacts from Leguminous crop	7.64E+01	48.37785	0
Total	2.94E+03	1.78E+03	1.56E+03

Appendix T

Table T-1 Cradle-to-harvest gate impact assessment data for freshwater acidification (including all "Nutrient Application" contributions) expressed as kg SO_2 eq associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean in Eastern Canada (Ontario and Quebec)

Contributions	**Wheat**	**Corn**	**Soybean**
Nitrate	2.09E-10	6.68E-11	6.16E-11
Ammonia	9.26E-11	2.76E-11	2.60E-11
Nitrogen Oxides	1.58E-11	4.70E-12	4.43E-12
Green Manure	2.57E-12	9.64E-14	6.82E-13
Manure	1.45E-12	7.89E-13	6.39E-13
Cover Crops	0.00E+00	1.52E-12	0.00E+00
Mineral Amendments	0.00E+00	7.06E-13	7.79E-15
Field Operations	3.78E-12	2.12E-12	2.95E-12
Seed Inputs	3.49E-12	2.20E-13	5.10E-13
Impacts from Leguminous Crop	6.49E-13	6.43E-13	0.00E+00
Total	3.29E-10	1.05E-10	9.68E-11

Appendix U

Table U-1 Cradle-to-harvest gate impact assessment data for freshwater eutrophication (including all "Nutrient Application" contributions) expressed as kg PO_4^- eq associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean in Eastern Canada (Ontario and Quebec)

Contributions	**Wheat**	**Corn**	**Soybean**
Phosphate	5.64E-03	0.001745	0.00406
Green Manure	0.001267	3.70E-05	0.000278
Manure	0.00193	0.000832	0.001047
Cover Crop	0	0.001083	0
Mineral Amendments	0	0.000467	5.28E-06
Field Operations	0.000725	4.01E-04	0.000557
Seed Inputs	0.0025	8.93E-05	0.001186
Impacts from Leguminous Crop	0.000199	0.000394	0
Total	1.23E-02	5.05E-03	7.13E-03

Appendix V

Table V-1 Cradle-to-harvest gate impact assessment data for land occupation (biodiversity) (including all “Nutrient Application” contributions) expressed as m^2 arable land eq. yr associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean in Eastern Canada (Ontario and Quebec)

Contributions	**Wheat**	**Corn**	**Soybeans**
Green Manure	0.7	0.02	0.2
Manure	1.7	0.9	0.9
Cover Crop	0	0.5	0
Mineral Amendments	0	1.9	0.01
Field Operations	1.3	0.8	1.1
Seed Inputs	0.3	0.03	0.2
Impacts from Leguminous Crops	0.1	0.1	0
Total	4.0	4.2	2.3

Appendix W

Table W-1 Cradle-to-harvest gate impact assessment data for water scarcity (including all "Nutrient Application" contributions) expressed as m^3 world-eq associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean in Eastern Canada (Ontario and Quebec)

	Wheat	**Corn**	**Soybean**
Green Manure	19.6	0.4	2.4
Manure	62.1	29.9	25.7
Cover Crop	0.0	18.5	0.0
Mineral Amendments	0.0	81.9	0.0
Field Operations	13.8	8.4	11.1
Seed Inputs	136.2	1.8	50.4
Impacts from Leguminous Crops	3.0	3.7	0.0
Total	234.7	144.5	89.6

Appendix X

Table X-1 Cradle-to-harvest gate CCLT emissions expressed as kg CO_2 eq associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean averaged by "low yield" and "high yield". Key contributing parameters include "Soil Carbon Change" (CO_2 emissions), field-level nitrous oxide emissions, animal manure application, organic amendments, green manures, cover crops, impacts from leguminous crop, "Field Operations" (farm machinery using during production), and "Seed Inputs" (seed provision).

	Wheat		**Corn**		**Soybean**	
Contributions	Low Yield <3.9 t ha^{-1}	High Yield >3.9 t ha^{-1}	Low Yield <10.1 t ha^{-1}	High Yield >10.1 t ha^{-1}	Low Yield <2.8 t ha^{-1}	High Yield >2.8 t ha^{-1}
Soil Carbon Change	-660.8	-145.8	-218.3	-100.4	-447.1	-142.6
Nitrous Oxide	820.0	675.4	246.6	222.7	45.8	282.2
Green Manure	75.7	23.3	1.0	3.4	2.1	21.4
Manure	30.3	61.4	33.4	11.8	0.2	22.5
Cover Crops	0.0	0.0	0.0	52.3	0.0	0.0
Mineral Amendments	0.0	0.0	0.0	26.1	0.0	0.7
Impacts from Leguminous crop	0.0	20.9	12.2	0.0	0.0	0.0
Field Operations	90.9	83.3	33.7	66.0	65.6	70.1
Seed Inputs	39.4	18.9	1.9	3.1	20.6	13.6
Total	395.6	737.3	110.5	284.9	-312.8	267.8

Appendix Y

Table Y-1 Cradle-to-harvest gate CCLT emissions expressed as kg CO_2 eq associated with the production of 1 t of crop harvested of organic wheat, corn, and soybean averaged for Ontario and Quebec. All key contributing parameters include "Soil Carbon Change" (CO2 emissions), field-level nitrous oxide emissions, animal manure application, organic amendments, green manures, and cover crops, "Field Operations" (farm machinery using during production), "Seed Inputs" (seed provision), and "Impacts from Leguminous Crop".

	Wheat		**Corn**		**Soybeans**	
Contributions	ON	QC	ON	QC	ON	QC
Carbon Dioxide	-366.2	-663.5	-105.7	-233.9	-271.7	-193.3
Nitrous Oxide	339.4	1549.2	207.3	274.7	287.1	161.1
Green Manure	59.5	50.7	3.8	0.0	29.5	5.6
Manure	14.7	91.3	11.5	38.1	21.7	12.0
Cover Crops	0.0	0.0	45.3	0.0	0.0	0.0
Mineral Amendments	0.0	0.0	22.6	0.0	1.1	0.0
Impacts from Leguminous crop	7.4	8.3	0.0	14.7	0.0	0.0
Field Operations	81.6	100.0	59.7	36.7	89.9	52.5
Seed Inputs	24.5	45.4	2.2	3.0	18.5	13.2
Total	160.9	1181.4	246.7	133.1	176.2	51.2