Life Cycle Assessment of Organic Canadian Prairie Field Crop Systems: Oats, Rye, and Wheat

By

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ABSTRACT

Organic farming is a rapidly growing agricultural sub-sector in Canada that many look to as a means to lower resource use and environmental impacts of food systems. In this thesis, life cycle assessment (LCA) is coupled with modeling of changes in soil organic carbon (SOC) to quantify impact contributions from Western Canadian organic wheat, rye and oats production to a range of global scale challenges including climate change. Primary data were collected using a survey sent to organic field crop producers across Canada. Options for modelling SOC flux were examined through a literature review. Results indicate that net climate change impacts, on a production weighted average basis, were 79.6 kg CO_2 eq tonne^{-1} of wheat, 134 kg CO_2 eq for oats, and 116 kg CO_2 eq for rye. Notably, some individual organic farms were sequestering SOC, but this was not enough to make any of the farms net negative.

LIST OF ABBREVIATIONS USED

AB = Alberta

ac^{-1} = per acre

AEZ-EF = Agro-ecological Zone Emission Factor Model

AFNOR = Association Française de Normalisation

ag = agriculture

APOS = allocation at the point of substitution

BC = British Columbia

C = carbon

°C = degrees Celsius

CA = Canada

CC = climate change

CCOF = California Certified Organic Farmers

CH - Switzerland

CH_4 = methane

CO_2 = carbon dioxide

CO_2eq = carbon dioxide equivalent

CSRC = Canadian Roundtable for Sustainable Crops

CTUe = comparative toxic unit equivalent

DBC = dichlorobenzene

DNDC = DeNitrification-DeComposition Model

EF = emissions factor

e.g. = example

EPA = Environmental Protection Agency

EPIC = Environmental Policy Integrated Climate Model

EU = fossil and nuclear energy use

et al. = et alia (and others)

FAO = Food and Agriculture Organization

FA = freshwater acidification

FE = freshwater eutrophication

FU = functional unit

FX = freshwater ecotoxicity

g = grams

GLO = global

GM = green manure

GREET = Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model

GTP = global temperate potentials

GWP = global warming potential

ha = hectare(s)

ha^{-1} = per hectare

HRS - hard red spring

IFA = International Fertilizer Association

IPCC = Intergovernmental Panel on Climate Change

i.e. = id est (that is)

ISO = International Organization for Standardization

K = potassium

kg = kilogram

kg^{-1} = per kilogram

km = kilometer(s)

K_2O = potassium oxide

lbs = pound(s)

LCA = life cycle assessment

LCI = life cycle inventory

LCIA = life cycle impact assessment

LMP = land management practices

LO = land occupation

m^2 arable land eq-yr = meters squared of arable land equivalent per year

MB = Manitoba

MJ = megajoule

mol^{-1} = per mole

n = sample size

N = nitrogen

NASA = National Aeronautics and Space Administration

NB = New Brunswick

NDC = Nationally Determined Contributions

NH_3 = ammonia

NL = Newfoundland and Labrador

N_2O = nitrous oxide

NO = nitrogen oxide

NO_2 = nitrogen dioxide

NO_3^- = nitrate

NO_x = nitrogen oxide(s)

NIR = National Inventory Report

NPK = nitrogen - phosphorus - potassium content (%) of manures and fertilizers

NS = Nova Scotia

OECD = Organization for Economic Co-operation and Development

ON = Ontario

P = phosphorus

PEI = Prince Edward Island

P_2O_5 = diphosphorus pentoxide

PO_4^{3-} = phosphate

PO_4eq = phosphate equivalent

QC = Quebec

REDCap = Research Electronic Data Capture

ROW = rest of world

RU = reconciliation unit

S = systems process

SALCA-P = Swiss Agricultural Life Cycle Assessment - Phosphorous

SK = Saskatchewan

SMS = Short Message Service

SOC = soil organic carbon

SO_2eq = sulfur dioxide equivalent

SWAT = Soil and Water Assessment Tool

t = metric tonne(s)

t^{-1} = per metric tonne

U = unit process

US = United States of America

USDA = United States Department of Agriculture

yr = year

yr^{-1} = per year

YT = Yukon

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CHAPTER 1: INTRODUCTION

1.1 Overview

Continuous pressure is being placed on agricultural land and resources as food demands are projected to double in the 21st century (Spiertz, 2012). With a population rising to beyond 9 billion by 2050 and developing countries shifting their diets to high-value foods and meats, there is a rapid need to meet these growing food demands and to do so with limited environmental consequences (Bahadur et al., 2018; Hofstrand, 2014; Spiertz, 2012). Currently, the agriculture sector is the source of about 18% of total global anthropogenic greenhouse gas emissions (GHG) (including forestry and land use) (Ritchie et al., 2020), and is a major contributor to a range of natural resource depletion concerns including eutrophying emissions, water resource depletion, damage to terrestrial and aquatic ecosystems (Poore and Nemecek, 2018), and more. The compounding GHG emissions continue to raise global temperatures which intensify already-arduous climate change impacts such as droughts and heat waves, sea level rise, and increases in storms and their intensity (IPCC, 2022; NASA, 2022a). To mitigate climate change impacts, anthropogenic GHG emissions need to diminish dramatically (IPCC, 2022) and the agriculture sector is a prime target for emissions reduction and improvement in environmental efficiency. In Canada, the agriculture sector is responsible for 10% of the nation's total GHG emissions (Environment and Climate Change Canada, 2021a; Environment and Climate Change Canada 2021b) and as such represents potential opportunity for climate change mitigation solutions (Drever et al., 2021). Harnessing these opportunities in agriculture could not only help reduce sector emissions, but it could help contribute to Canadian-specific, and global, climate targets of limiting the rising global temperatures to 1.5 °C (Environment and Climate Change Canada, 2016).

Historically, issues of concerns related to conventional farming methods have included loss and degradation of soils; high use of chemical fertilizers, pesticides, etc. (Clark and Tillman, 2017; Nicoletti, 2021; Spiertz, 2009). Often, alternative agricultural production systems are looked at to produce food with lower resource and environmental impacts than conventional practices (Baker et al. 2013; Suddick et al., 2011; Venkat, 2012). One well-established alternative farming approach, organic production, can address many of these concerns (Lotter 2003; Muller et al., 2017; Reganold and Wachter, 2016) and as a result its implementation has grown rapidly due to demand from an increasing number of consumers seeking organic products (Agriculture and Agri-Food Canada, 2021c). However, many studies that have attempted to compare the environmental performance of organic and conventional agricultural practices (for example Kokare et al., 2014; Przystalski et al., 2008; Reid et al., 2011; Seufert and Ramankutty, 2017; among others) have been inconclusive, with relative impacts varying by issue of concern, geography, crop, or management practice. For example, a life cycle assessment study of Canadian production of oats suggests that a shift in production practices from conventional to organic agriculture would not “systematically decrease environmental impacts” (Viana et al., 2022, p. 1), while other analysis have shown mixed results (e.g., Cooper et al., 2011; Knudsen et al., 2014; Verdi et al., 2022).

These mixed results could be due to actual differences or as a result of methodologies applied. Thus, a holistic and systems-level understanding of organic farming systems, and other alternative management practices, and their impacts is necessary to characterize their environmental performance. Life cycle assessment (LCA) is an International Organization for Standardization (ISO) standardized method used to assess contributions to a range of global- to regional-scale resource depletion and environmental concerns that arise from a product or service (ISO, 2016a). Although the scope of issues it is suited to address is limited, LCA has become the preeminent method for robustly and transparently assessing a wide range of concerns relevant to understanding the performance of agricultural systems (Government of Alberta, 2022; Sustainable Agriculture Research & Education Program, 2018). This includes greenhouse gases, eutrophying and acidifying emissions, along with resource depletion concerns, including land and energy use (Poore and Nemecek, 2018). Consequently, to date, LCA has been used to understand life cycle impact contributions from thousands of food systems across the globe (Lu and Halog, 2020; McAuliffe et al., 2020; Poore and Nemecek, 2018, among others).

Despite their rising prominence, organic systems are not as prevalent in the LCA literature, particularly in the Canadian context. A literature review of organic field crop systems from Bamber and colleagues (2022) revealed only 22 LCA studies published between 2010 and 2021 assessed the performance of organic field crop systems and none of the studies characterized organic production of those crops in Canada (Bamber et al., 2022). Since its publication, however, Viana and colleagues (2022) have reported results of an LCA that assessed potential impacts from the transition from conventional to organic oat production in Quebec. Hence, an important gap exists in relation to understanding the life cycle environmental performance, and in particular the GHG emission implications, of organic field crop production in Canada.

Understanding the environmental performance of Canadian organic field crop emissions is of particular importance in the Prairie provinces of Alberta, Manitoba and Saskatchewan, which encompasses 81% of the nation's total organic field crop acreage (Canada Organic Trade Association, 2017). The Prairie provinces and their domination in organic field crop production in Canada also represent an prospective opportunity for carbon sequestration in agricultural soils, given the historical legacy of soil decarbonization under earlier decades of management and some of the common practices used in organic agricultural including conservation tillage (Apezteguía et al., 2009; Chan, 2008; Mazzoncini et al., 2011; Piccoli et al., 2016; Wang et al., 2011; Wuaden et al., 2020), use of cover crops (Mazzoncini et al., 2011; Novara et al., 2019; Olson et al., 2014) and residue incorporation (Dolan et al., 2006; Han et al., 2018; Lehtinen et al., 2014; Piccoli et al., 2016). Incorporating SOC-sequestering management practices has been identified as a potentially substantial natural climate change solution that can be adopted by Canadian farmers (Drever et al., 2021) helping to reduce Canada's overall emissions and meet its climate targets. However, to date there is limited published research that incorporates measured or modelled changes in SOC into LCA. This is, in part, because there is no clearly defined procedure for incorporating changes in SOC in life cycle assessment studies (Bessou et al., 2020; Goglio et al., 2015). Studying soil organic carbon flux and its impact on agricultural systems is imperative, yet there exists a gap surrounding how soil organic carbon is modelled in life cycle assessments.

1.2 Objectives

This research aims to advance understanding of the life cycle environmental impacts of Western Canadian cereal crop production under organic management that incorporates changes in SOC as part of the quantification of net GHG emissions. This work is part of a larger research project that set out to assess the net GHG emissions, along with a suite of other environmental impacts, of Canadian field crop production under organic management more generally. The objectives of this thesis are the following:

1) Explore the literature surrounding current modelling approaches to soil organic carbon in the life cycle assessment context, specifically:
    a. Characterize and evaluate current approaches to modelling soil organic carbon in conjunction with life cycle assessment studies;
    b. Assess how each soil organic carbon modelling approach estimates changes in SOC resulting from land management practices; and

c. Explore differences and potential challenges in how soil organic carbon is modelled in organic versus conventional systems.

2) Quantify the net life cycle greenhouse gas emissions and life cycle environmental impacts that arise from Canadian Prairie oat, rye, and wheat cropping systems reported on a production output weighted average basis. Specifically:

   a. Identify the impacts contributions associated with the impact categories (identified through a literature review and LCI data collection to be) climate change (long term), fossil and nuclear energy use, freshwater acidification, freshwater ecotoxicity, freshwater eutrophication, and land occupation. And,

   b. Determine the contribution of SOC under current organic management practices to total environmental emissions.

By addressing these objectives, this research helps advance the understanding of the environmental performance of organic field crop production generally and more specifically in Canada while contributing to efforts to better incorporate changes in SOC into LCA of agricultural production in general. This will bolster future modelling and predictions of Canadian organic crops, and the insights of these analysis could be used by decision-makers, researchers, and to make agricultural policies. Furthermore, data-driven estimates of global warming potential and other environmental impacts of organic crop production is important for informed consumers. Over time, and in combination with similar research, consumers could have access to a spectrum of environmental impacts of their Canadian-based food products, both conventional and organic, and can make purchasing choices accordingly.

While this thesis explores only the Prairie region of Canada, a 'sister' thesis by Shenali Madhanaroopan at the University of Waterloo explores the net greenhouse gas emissions and other life cycle environmental impacts of Canadian organic field crop production undertaken in the Eastern Canadian (Ontario/Quebec) region. Together, these two theses produced from data collected on Canadian organic field crops help to paint a more robust picture of the environmental performance of contemporary organic agriculture in Canada.

1.3 Thesis Structure

The balance of this thesis consists of three chapters which address the two main objectives. Chapter 2 has been prepared with input from Dr. Peter Tyedmers, Dr. Nathan Pelletier, and Dr. Goretty Dias. The paper arose out of the need to identify a tool for modelling soil organic carbon flux, particularly where a variety of land management practices are in use, including those in organic farming. Thus, this chapter describes the systematic literature review used to examine current approaches to modelling soil organic carbon flux. The paper was accepted for an oral presentation at the 2022 LCA Foods Conference in Lima, Peru and was presented in October 2022 with a published extended abstract in the conference proceedings.

Chapter 3 addressed the central question motivating this research into understanding the net greenhouse gas emissions and other life cycle environmental impacts associated with organic field crop production in the Canadian Prairies. The paper details the cradle-to-harvest gate LCA methods including details of the calculations, modelling with openLCA and Holos, and then reports the life cycle impact assessment results and their interpretation. Chapter 3 also features several sensitivity analyses with Holos, emissions factors, and green manures. Moreover, it also details how results of this analysis compare to relevant data found in the literature. Chapter 3 concludes with study implications, limitations, and contributions. This paper was written with contributions from Shenali Madhanaroopan and input from Dr. Peter Tyedmers, Dr. Goretty Dias, Dr. Nathan Pelletier, and Nicole Bamber.

Chapter 4, the final chapter, provides a discussion of the research collectively and the overall contribution to the literature. It also discusses overall themes throughout the research including areas for future research.

CHAPTER 2: SOIL ORGANIC CARBON IN LIFE CYCLE ASSESSMENT: MODELLING APPROACHES, LAND MANAGEMENT PRACTICES, AND ORGANIC SYSTEMS

2.1 Introduction

Climate change is a persistent threat with irreversible consequences should global warming exceed a threshold of 1.5 °C above pre-industrial levels (IPCC, 2018). Urgent and rapid action is necessary to mitigate against the impacts of climate change, and avoid more dire consequences (IPCC, 2022). Therefore, deep cuts to global anthropogenic greenhouse gas (GHG) emissions are critical to meet world emission reduction targets and prevent catastrophic climate change impacts. A large portion of global emissions originate from the agriculture sector: about 18.4% in 2016 (Ritchie et al., 2020). Importantly, however, this sector not only represents a large source of current emissions, but also a potential domain for climate change mitigation solutions (Drever et al., 2021; Fargione et al., 2018).

To meet the growing food demand of a rising population, and agriculture's historic dependence on activities that result in direct (e.g. from soil disturbance) and indirect (e.g. from fossil fuel combustion) emissions, it is clear why agriculture contributes substantially to climate change. In addition to emissions, agriculture also makes substantial contributions to a wide range of resource depletion and environmental concerns. These include biodiversity loss (Maxwell et al., 2016), depletion and degradation of freshwater resources (Peters and Maybeck, 2000), and damaging terrestrial and aquatic ecosystems, among others (Poore and Nemecek, 2018). Given the many environmental challenges of agriculture, it is not surprising that less impactful practices are being proposed, deployed, and studied, including those that decrease or even sequester greenhouse gases through the creation of GHG sinks (Abbas et al., 2020; Bai et al., 2019; Kimble et al., 2016; Madhanaroopan, 2022; West and Marland, 2002). Hence, understanding food system emissions, including potential sequestration of carbon, is essential for advancing less impactful agriculture production systems and subsequently mitigating climate change. Knowledge surrounding sustainable production practices will also help decision-makers and consumers in making more informed decisions surrounding policies or choices at the grocery store.

Life cycle assessment (LCA) is a biophysical accounting framework (ISO, 2016a, ISO, 2016b) frequently chosen to model a range of resource depletion and environmental impacts of agriculture, and food systems more generally, including contributions to climate change (Haas et al., 2000; Poore and Nemecek, 2018) along with potential impact reduction strategies (Finnveden et al., 2009). Though thousands of studies have used LCA to estimate emissions and other environmental impacts of agricultural systems, until relatively recently the potential climate impacts of changes in soil organic carbon (SOC) and the impact that this has on atmospheric CO_2 concentrations has been absent from many of these studies, most notably due to a lack of measured change in soil carbon or robust procedures for modeling soil organic carbon in life cycle assessments (Bessou et al., 2020; Goglio et al., 2015). Hence, LCA practitioners who want to assess the climate change impacts from a loss of SOC or the mitigation potential of an agricultural system via sequestration, are left with a lack of understanding on how to deal with complex SOC models. Given the importance of agricultural systems as both carbon sources and potential sinks, an exploration of soil organic carbon modelling approaches in life cycle assessment studies is vital to determine the role of soil carbon sequestration within agricultural systems in climate change mitigation solutions.

2.2 Background

2.2.1 Soil Organic Carbon

Soil organic carbon results from the interactions between photosynthesis, decomposition, and respiration (Ontl, 2012). It is directly related to soil organic matter, (decomposed material that originated from any living organism (Bot and Benites, 2005)) and results “directly from growth and death of plant roots, as well as indirectly from the transfer of carbon-enriched compounds from roots to soil microbes” (Ontl, 2012). SOC rates vary widely in both managed and undisturbed soils as a function of soil particle size, climate and vegetation. It is a critical aspect of healthy soils as it contributes to a number of soil processes important to agriculture including erosion resistance, water filtering, nutrient cycling, and more (Bessou et al., 2020). Soils are important reservoirs of carbon, but have also been a significant source of anthropogenic CO_2 released to the atmosphere, as soils were disturbed globally over recent centuries; thus, attention has turned to the potential for agricultural soils to be managed to mitigate climate change through increased SOC sequestration (Lal, 2004; Lal et al., 2007). However, the true scope and extent of SOC as a means of atmospheric CO_2 sequestration remains unclear (Amundson & Biardeau, 2018; Popkin, 2021; Powlson et al., 2011). Despite this, many governments and other actors are making important climate change mitigation policy choices that rely on the potential for soil carbon sequestration. For example, Drever and colleagues (2021) conclude that agriculture is Canada’s best opportunity for natural climate solutions. Needless to say, it is crucial to include SOC changes in agricultural LCA using accurate and appropriate modelling techniques.

Whether or not soil carbon sequestration can be relied on as a long-term climate change mitigation solution, there are multiple co-benefits of sequestration that highlight its importance in agricultural systems and its necessity in future studies. The benefits of healthy soil C stocks include “advancing food and nutritional security, increasing renewability and quality of water…strengthening elemental recycling (Lal et al., 2015, p. 79), species conservation (Flores-Rios et al., 2020), and increased biodiversity (De Beenhouwer et al., 2016; Lal et al., 2015; Miles et al., 2009), among others. These co-benefits of maintaining, and ideally increasing soil organic carbon, further illustrate the importance of including SOC fluxes in agricultural studies. This is particularly true for LCA studies which capture a wide variety of environmental impacts and emissions.

2.2.2 Life Cycle Assessment

The need for understanding agricultural production on a holistic scale requires a systems-level tool that accounts for a diverse assortment of inputs, outputs, and production practices (Bamber et al., 2022). Life cycle assessment (LCA) is a standardized methodology used to assess contributions to a range of resource depletion (energy use, land use, water use, etc.), and environmental degradation concerns (climate change, ozone depletion, acidification, etc.) that arise from the provision of products and systems throughout their life cycles (ISO, 2016a, ISO, 2016b). In addition to facilitating the quantification of contributions to these global-scale challenges, LCA allows for the identification of environmental ‘hotspots’, activities that make substantial or disproportionate contributions to overall impacts within the boundaries of an analysis, which facilitates efforts for targeted improvements to reduce environmental impacts (Finnveden et al., 2009). Though applied originally to understand the impact contributions of manufactured products, over recent decades, LCA has been used increasingly to assess the resource and environmental degradation impacts of agricultural systems. For example, one available agricultural database, Agribalyse, contains 11,393 agricultural life cycle inventory data sets alone (OpenLCA Nexus, 2022). Despite its increased use in quantifying impacts of agricultural products, it still remains a challenging exercise due to the complexity of natural processes and the carbon and nitrogen biogeochemical cycles.

The variety of impact categories assessed within existing LCA studies allow for comparison of environmental impacts between cropping systems, management practices, etc., where the methods and assumptions used in studies are consistent (Haas et al., 2000; Ziegler et al., 2022). Within agricultural LCA studies, most studies report results for a common set of impact categories. These typically include global warming potential, acidification potential, eutrophication potential, and cumulative energy demand (Parker, 2022). There is a particular emphasis placed on contributions to climate change (i.e., global warming potential) with this impact category being included in 98.4% of agricultural LCA case studies (n=1,015) (Parker, 2022). Moreover, it is well documented that major sources of greenhouse gas emissions from agricultural LCA studies include the production of synthetic fertilizers, livestock production along with manure management, and enteric fermentation where these occur (Agriculture and Agri-food-Canada, 2020; EPA, 2015; FAO, 2018; Livestock and Poultry Environmental Learning Community, 2019; Ritchie, 2020; Russell, 2014). Despite the richness of agricultural LCA studies and depth of data available on food system contributions to climate change, there is a glaring absence of the quantification of soil organic carbon fluxes in many of these studies (Bessou et al., 2020; Goglio et al., 2015). This points to a gap in understanding the scale of GHG emissions from many systems that are currently losing SOC, as well as the climate mitigation effect of other agricultural systems in which SOC is actively being sequestered, however temporarily. Given the potential scale of both soil carbon sequestration and loss rates in agriculture, there needs to be an understanding of how to model SOC impacts in LCA studies.

A specific interest exists within efforts to model impacts of organic and field cropping systems. For example, van der Werf and colleagues (2020) suggest that much

LCA practice does not accurately capture differences in environmental impacts between organic and conventional systems. Moreover, organic agriculture is rising in popularity as consumers seek products from production methods that address animal welfare, environmental issues, and food contaminant issues (Peng, 2019). Therefore, studying SOC fluxes within LCAs of both organic and conventional production practices could help create a more holistic picture of environmental impacts: making comparison between agricultural management practices more accurate.

In addition to the importance of organic systems, field crop systems provide extensive opportunity for understanding the role of soil organic carbon fluxes on a significant scale. For instance, Canada, a large field crop producer globally, currently has 21 million hectares of land under field crop production (Agriculture and Agri-Food Canada, 2021c). On a global scale, field crop systems contribute significantly to land use, energy use, and other areas of resource consumption (FAO, 2003; Spiertz and Ewert, 2009; van der Werf, 2004). Nonetheless, these vast field cropping systems represent a global opportunity for potential climate change mitigation solutions. Land management practices (LMP) such as no- and conservation-tillage have been shown to increase soil organic carbon levels relative to previously depleted levels that resulted from decades of heavy tillage (Apezteguía et al., 2009; Chan, 2008; Mazzoncini et al., 2011; Piccoli et al., 2016; Wang et al., 2011; Wuaden et al., 2020). Other LMP such as residue incorporation (Dolan et al., 2006; Han et al., 2018; Lehtinen et al., 2014; Piccoli et al., 2016), cover crops (Mazzoncini et al., 2011; Novara et al., 2019; Olson et al., 2014) and other sustainable management practices have also been shown to increase SOC levels in certain settings. This highlights the importance of not only incorporating the use of SOC modelling into LCA studies generally, but understanding SOC fluxes of field cropping systems, in particular, and the role of land management practices on SOC dynamics.

2.2.3 Previous Work Reviewing Soil Organic Carbon Modelling in LCA

Despite their importance, SOC fluxes have historically been left out of LCAs of agriculture in large part due to a lack of clearly defined and widely adopted procedures for modelling these fluxes (Joensuu et al., 2021; Goglio et al., 2015). A 2015 study by Goglio and colleagues attempts to fill some of the above-identified gaps by reviewing "various methods used to estimate soil C changes…of agricultural LCAs" (Goglio et al., 2015, p. 23). In addition to reviewing the various SOC modelling methods, the study looks at ways changes in SOC from land management changes and land use changes are modeled (i.e., land management practices). The results reveal a variety of SOC modelling approaches used to provide inputs to life cycle inventories that include simple carbon (C) models (such as the Introductory Carbon Balance Model) and dynamic crop-climate-soil models (such as the DeNitrification DeComposition model). The paper concludes with a recommendation that soil organic carbon flux be a soil quality indicator included amongst impact categories when conducting LCAs (Goglio et al., 2015). Since the study's publication, new SOC modelling approaches have emerged. Moreover, given the rising prominence of LCA as a tool for quantitative evaluation of most direct and indirect sources of GHG emissions from agriculture, and the persistent lack of clarity regarding how changes in SOC might best be assessed within an LCA framework, this paper sets out to (1) review and update the range of SOC estimation tools used to assess changes in SOC within the context of current agricultural LCA field crop research, (2) identify the range of land management practices that were modelled on farms studied, and (3) determine the organic studies' SOC modelling approaches and specific modelling challenges that may exist for modelling SOC in the organic production context.

2.3 Methods

2.3.1 Literature Review

To understand the current approaches to modelling SOC fluxes in the agricultural LCA field crop context, a literature review was conducted using the Scopus database. Two search strings were used to assemble the most comprehensive search results; the first search encompasses general LCAs of field crops while the second is a finer-grained approach attempting to capture SOC-specific LCAs.

- "LCA" OR "life AND cycle AND assessment" OR "life AND cycle AND analysis" OR "carbon footprint*" OR "environmental footprint*" AND "corn*" OR "pea*" OR "oat*" OR "lentil*" OR "potato*" OR "wheat" OR "hay" OR "grain*" OR "cereal*" OR "oilseed*" OR "barley" OR "rye" OR "soy" OR "soybean*" OR "maize" OR “maise” OR "pulse*"
- "LCA" OR "life AND cycle AND assessment" OR "life AND cycle AND analysis" OR "carbon footprint*" OR "environmental footprint*" AND “soil AND organic AND carbon” OR “soil AND carbon AND flux” OR “soil AND carbon” OR “carbon flux” AND "corn*" OR "pea*" OR "oat*" OR "lentil*" OR "potato*" OR "wheat" OR "hay" OR "grain*" OR "cereal*" OR "oilseed*" OR "barley" OR "rye" OR "soy" OR "soybean*" OR "maize" OR “maise” OR "pulse*"

Rice was excluded from this field crop list because, as a semi-aquatic plant, it requires a unique set of growing conditions and practices relative to that of other grains and field crops (Think Rice, 2020). Moreover, the top rice producing countries include China, India, and Indonesia respectively (USDA, 2022) which are all beyond the scope of this study.

Results from the first and second search strings were compiled to create one comprehensive and inclusive list of papers that fit all search criteria. The two search strings yielded a combination of over 25,000 papers that needed narrowing down to a manageable scope. To ensure that the most modern modelling techniques were showcased while straddling the earlier review work undertaken by Goglio and colleagues (2015), this review excluded studies that were published prior to 2010, thereby only including studies published between 2010 and June, 2022. Geographically, the focus was on studies that were undertaken within agricultural settings that shared broadly similar climate and soil types to those found in the USA and Canada, determined based on a global soil map (USDA, 2005). The resulting country-specific study inclusion criteria were:

- Albania, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, UK, and USA.

Some countries, which broadly share a similar climate to either the USA or Canada, such as China, were excluded from this group as too much of their agricultural soils were deemed dissimilar to those in the USA or Canada (or there were no published studies from these countries that fit the search criteria).

To narrow the scope further, document types were narrowed to include only English language articles and conference papers. In addition, papers that aligned with several disciplines were excluded. Specifically, the following disciplines were not included:

- Arts and humanities, computer science, decision sciences, dentistry, health professions, mathematics, medicine, neuroscience, nursing, psychology, and veterinary.

With these final filters applied, a total of 4,249 candidate papers remained to be reviewed individually to ensure alignment with the objectives of this review effort. The papers needed further narrowing due to many false positives, including those whose geographic setting was beyond scope, non-LCA studies, and studies that were not specific to field crops. Titles of all candidate papers were initially reviewed for conformance with the high-level inclusion criteria related to substantive discipline and geographic setting of analysis. Papers that did not conform were excluded.

More detailed screening was then conducted to exclude papers which did not: a) apply LCA methods, b) also assess change in SOC and c) apply their analysis to one or more field crops. Detailed screening preceded as follows. Abstracts of candidate papers were initially reviewed. If no mention of either use of LCA or measurement of change in SOC was made in the abstract, the paper's methods section was read looking for the same components. Finally, an additional word search was conducted in candidate papers using the keyboard function "ctrl + f" and searching for the words "life cycle" and "soil" and "carbon" and "sequestration". Papers were further rejected if they did not include the LCA methodology, and they did not account for soil organic carbon. The final list of papers includes studies published between 2010 and 2022 and combined LCA methods with at least one technique to model or estimate SOC fluxes from soil as part of assessing emissions from field crop production in a mid-latitude agricultural setting. The final number of papers that were included in the full analysis was 121 (Appendix A).

2.3.2 Characterizing SOC Modelling Techniques

All final retained papers were read closely to understand and categorize their applied SOC change modelling approaches. Firstly, SOC quantification approaches identified with the literature review were broadly categorized based on the tool or modelling strategy used, or whether measurements from experiments were used. Categories include use of downloadable software, simple C models, and sampling. Downloadable software refers to SOC flux estimation/modelling which can be accessed via downloadable links, spreadsheets, or fillable online. Simple C models "are based on a set of simple equations, along with some details and evaluation categories" (Goglio et al., 2015, p. 25). Using the Goglio et al. (2015) definition of simple C models, some are a simple equation or set of equations, while some are more elaborate and widely recognized, such as the Introductory Carbon Balance Model (ICBM). The last category is called sampling. This includes all SOC flux estimation that involved in-the-field sampling and laboratory analysis. After the SOC modelling types were initially categorized, studies employing downloadable software and simple C models were investigated further to identify specific models and calculation approaches used and their frequency of use within the compiled literature.

To address the second objective, a sub-set of papers was examined for their application to understand SOC flux associated with different land management practices. Specifically, only studies that employed downloadable software SOC modelling techniques were reviewed for this objective as in the researcher's opinion, they represent the most diverse option for estimating SOC changes since they include process-based, empirical, and some embedded simple C models. Therefore, simple C models are excluded from the LMP analysis. Importantly, this part of the analysis reflects only those LMP that are specifically cited in the reviewed studies, not those that could in theory also be studied using the SOC modelling tools. In addition to the LMP assessed using SOC modelling techniques, a breakdown of the frequency with which each tool was used to simulate a particular LMP is included.

Lastly, a detailed evaluation of each of the downloadable software modelling approaches is provided. This includes a more in-depth look at what they assess/simulate, data requirements, and whether they are empirical or process-based. Importantly, the inclusion of empirical versus process-based approaches will also help inform an SOC modelling decision based on a researcher's availability of data, a study's spatial and temporal scale, relative comfort related to model uncertainty, and more (Adams et al., 2013). By understanding these finer-grained details of the models, LCA practitioners can be better informed when choosing a modelling approach for their study. For a comprehensive outlook of each of the identified downloadable software packages used to model changes in SOC, details regarding each of these tools, their origins, data requirements, and scope of application were sought from a close reading of the articles in which they were used in this review, article searches in which the tools were applied elsewhere, websites where the tools are described, and by contacting the developers or suppliers of the tools when those could be identified.

In addition to understanding the modelling approaches, papers identified in the literature review were also examined to determine whether conventional, organic, or both types of production practices were simulated with these modelling tools. This factor too will help LCA practitioners when selecting an SOC modelling approach based on production practices they wish to simulate.

2.4 Results

2.4.1 Frequency of Modelling Types

Of the 121 papers reviewed, 21 different methods to estimate the flux of SOC in mid-latitudinal agricultural systems were revealed. The high order modelling methods were categorized into downloadable software, simple C model, and sampling: all defined in Section 2.3.2 of this review. The findings of this categorization are graphed in Figure 1 below.

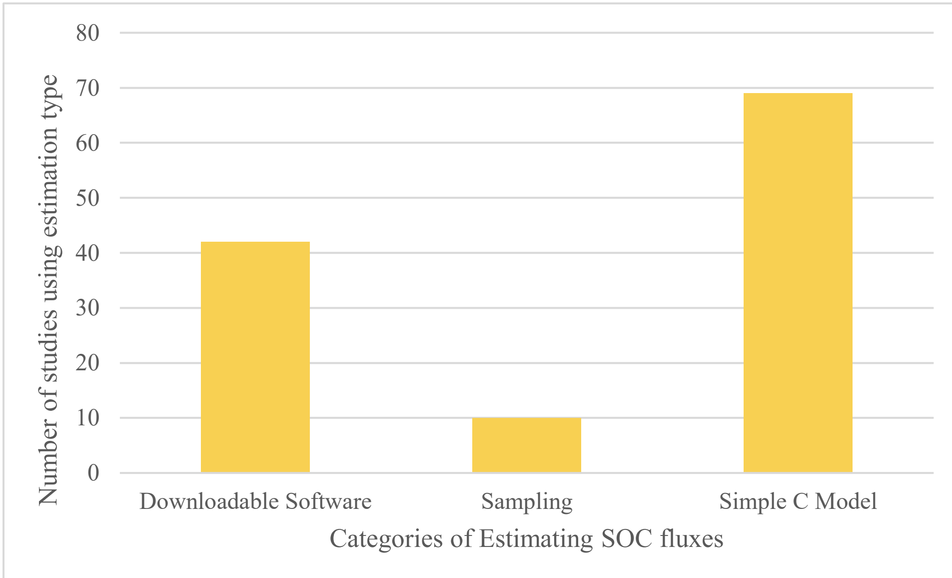

Figure 1. Frequency of modelling approaches used to estimate changes in the organic carbon content of agricultural soils used in life cycle assessment studies of field crop production in mid-latitude agricultural settings published between 2010 and 2022, categorized by downloadable software, simple C model, and sampling.

Amongst the three approaches, simple C models was used most frequently (n=69), followed by the use of downloadable software packages (n=42). The sampling technique was the least commonly employed method of estimating soil organic carbon fluxes in the LCA studies examined (n=10).

To understand further the downloadable software and simple C model approaches, a breakdown of the various models and calculation types are shown in Figures 2 and 3.

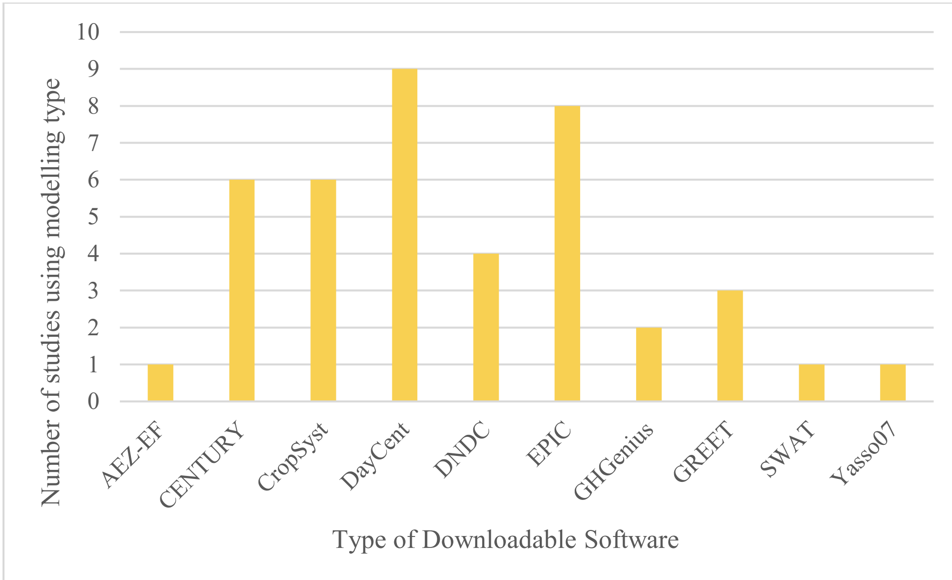

Figure 2. Frequency of downloadable software usage to estimate soil organic carbon flux in mid-latitude agricultural soils for LCA studies published between 2010-2022 where AEZ-EF = Agro-ecological Zone Emissions Factor Model; DNDC = Denitrification- Decomposition; EPIC = Environment Policy Intergraded Climate model; GREET = Greenhouse gases, Regulated Emissions, and Energy use in Technologies; SWAT= Soil and Water Assessment Tool.

In the downloadable software category, DayCent was the most frequently (n=9) used tool to assess soil organic carbon fluxes in association with the LCA methodology in mid-latitudinal agricultural soils (Figure 2). This is followed by EPIC (n=8), CropSyst and CENTURY (n=6 for both), DNDC (n=4), GREET (n=3), and GHGenius (n=2). Finally, AEZ-EF, SWAT, and Yasso07 all appear only once throughout the literature reviewed.

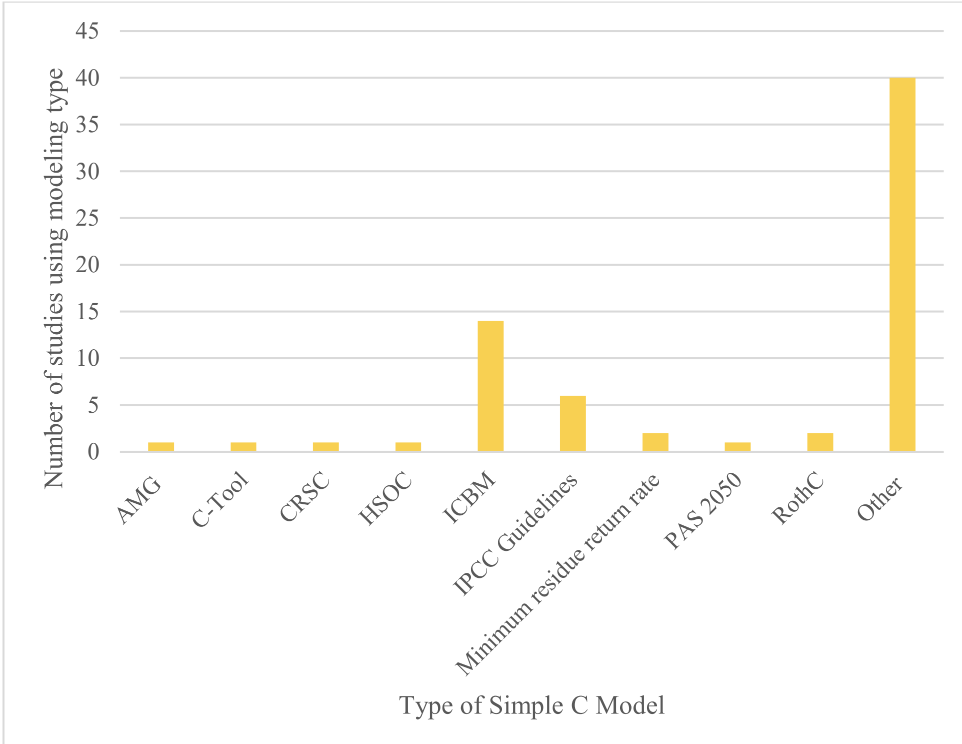

Figure 3. Frequency of Simple C model usage to estimate soil organic carbon flux in mid-latitudinal agricultural soils in LCA studies published between 2010-2022 where CRSC = Canadian Roundtable for Sustainable Crops; HSCO = Humified Soil Organic Carbon model; ICBM = Introductory Carbon Balance Model; IPCC = Intergovernmental Panel on Climate Change; PAS = Publicly Available Specification.

The most often used simple C model is categorized as 'other' (n=40) (Figure 3). This includes all instances where studies used a calculation-based approach that did not have an associated name or standard. The next most used simple C model was ICBM (n=14), followed by IPCC guidelines (n=6). 'Minimum residue return rate' and RothC models both appeared twice. The remaining simple C models each only appeared once throughout the literature reviewed (Figure 3).

It should be noted that all downloadable software models identified in the reviewed paper are not intended for modelling soil organic carbon change values. For example, GHGenius uses IPCC but is normally used for LCAs of biofuels. However, based on the information found within the literature review, authors identified using GHGenius to generate an SOC value. Furthermore, it should be noted that some downloadable software or simple C models may have other simple C models informing them.

2.4.2 Land Management Practices

Because certain land management practices have the capacity to increase the carbon sequestration potential of agricultural soils, choosing a modelling approach that has a track record of application to a variety of land management practices not only indicates a level of flexibility, but may aid in creating a holistic representation of farm procedures and soil interactions, including potential increases in SOC from LMP. As noted above, only downloadable software models used in modeling SOC fluxes were included in this land management practice analysis. The LMP analysis includes understanding which land management practices are simulated with each modelling approach (Table 1). While the modelling tools identified in the literature review may have the capability to simulate other LMP that are not cited in the table, Table 1 reflects only the LMP that are specifically cited in the literature reviewed.

Table 1. Frequency of simulated land management practices for SOC modelling approaches identified with the literature review. Green boxes denote the land management practice was simulated with that downloadable software, where red boxes denote the land management practice was not simulated with that downloadable software throughout the literature review. Numbers in the box indicate frequency of a particular downloadable software that simulated that land management practice.

Modeling Approach	Land Management Practices										
	Total Number of studies	Cover Crops	Crop Protection	Crop Rotation	Irrigation	Fertilizer	Land Use Change	Machinery Use	Manure	Residues	Tillage
AEZ-EF	n=1						1				
CENTURY	n=5	1	1		1	2	3	1	1	2	4
CropSyst	n=6		3	3	1	5		5		1	4
DayCent	n=9	1		3	2	5		2		2	5
DNDC	n=4			2	2	3		2		3	2
EPIC	n=8		1	4	2	2	1	3		2	4
GHGenius	n=2	1			1	1	1				2
GREET	n=3	1	100			2	2				1
SWAT	n=1	1	1	1		1		1			
Yasso07	n=1	1					1				

2.4.3 In-Depth Look at Downloadable Software Approaches

The literature review revealed 21 different modelling approaches to estimate the flux of soil organic carbon in the context of agricultural LCA studies. In total, 10 of these modelling approaches fall into the category of downloadable software packages. To understand these specific models in more detail, an overview of downloadable software approaches identified in the literature review is found below along with an examination of the models' inputs and other important factors which could help LCA practitioners in choosing an SOC modelling approach for their own study. Importantly, this analysis is not a comprehensive or complete summary of each model. Rather, it includes only information that could be found through research and contacting the models' creators and experts.

1) AEZ-EF Agro-ecological Zone Emission Factor Model

AEZ-EF refers to the Agro-ecological Zone Emission Factor Model developed by Plevin et al (2014). This model, according to its creators, is intended for use in conjunction with a static comparative economic model (Plevin et al., 2014). It is a carbon accounting model (Zhao et al., 2021) to "estimate the total CO_2-equivalent emissions from land use changes" (Plevin et al., 2014, p. 3). It accounts for sources of emissions including above-ground live biomass, soil organic matter, and harvested wood products, among other sources (Zhao, 2018). Amongst the reviewed studies, the AEZ-EF model was used once to study SOC flux associated with growing corn, soybeans for soy oil, and switchgrass in the USA and EU, simulating only the land management practice of land use change (Zhao et al., 2021).

2) CENTURY

The CENTURY model, developed by the United States National Science Foundation, is an agroecosystem modelling tool used to simulate various management practices and cropping rotations and their effect on agroecosystem sustainability (Metherell et al., 1993). Using inputs such as soil texture, initial soil carbon fraction, and monthly precipitation, among other variables, the CENTURY model depicts nutrient cycling and estimates fluxes of carbon, nitrogen, phosphorous, and sulfur in ecosystems such as grasslands, forests, and agricultural lands (Parton, 1996). This model is deemed appropriate for use in studying carbon (and other nutrients) dynamics, net primary production and the effects of climate change, and climate change scenarios (United Nations Framework on Climate Change, 2004). CENTURY is a process-based model meaning that it is a “representation of one or several processes characterizing the functioning of well-delimited biological systems of fundamental or economical interest” (Buck-Sorlin, 2013 p. 135). The literature review identified the CENTURY model’s use in six studies modeling production of corn and soybeans in the USA (Chen et al., 2018; Liu et al., 2020; Qin et al., 2016; Qin et al., 2018; Qin et al., 2021; Riazi et al., 2020). Land management practices simulated with the CENTURY model and cited in the literature review include use of cover crops, crop protection, irrigation, fertilizer and/or manure application, land use change, machinery use, retention of crop residues, and tillage.

3) CropSyst

CropSyst is a modelling tool that was developed to simulate and analyze cropping systems and their response to climate, management practices, and soils (Stöckle et al., 2003). This model has been applied to a multitude of crops and regions, simulating management practices such as irrigation, tillage, and crop rotation (FAO, n.d.). CropSyst outputs include examples such as a simulation of yield, soil erosion, and nitrogen budgets (Stöckle et al., 2003) in addition to soil organic carbon changes. The model is also process-based. CropSyst was used in six studies encompassed by this review to model wheat grown in the USA (Zaher et al., 2013), sorghum in Italy (Serra et al., 2017), potatoes and lentils in the USA (Adewale et al., 2016; Zaher et al., 2016), wheat in Europe (Monteleone et al., 2015b), and wheat in Italy (Monteleone et al., 2015a).

4) DayCent

DayCent is a process-based model and is a version of the CENTURY model that uses daily time-steps in contrast to the coarser time-period modelled using CENTURY (Colorado State University, 2012; Parton, 2005). The model has been used to simulate agricultural management practices in a variety of ecosystems, as well as simulating ecosystems in response to climate change (Necpálová et al., 2015). Further, the model simulates carbon and nitrogen fluxes among soil, vegetation, and the atmosphere (Colorado State University, 2012; Parton, 2005). DayCent includes sub-models such as plant production, allocation of net primary production, and water content and temperature in soil layers, for example (Necpálová et al., 2015). Inputs to the model include examples such as soil texture and daily precipitation, while outputs include soil organic carbon and net primary production, among others (Colorado State University, 2012). Soil organic carbon flux was estimated using the DayCent model in nine different studies in the literature review. These studies simulated cover crops, crop rotation, irrigation, fertilizer, machinery use, residues, and tillage. The studies used DayCent to model the following crops in the USA: corn (Adler et al., 2015; Jenkins and Alles, 2011; Khanna et al., 2020; Kløverpris et al., 2020; McKechnie et al., 2015; Nguyen et al., 2019; Riazi et al., 2018); soybeans (Khanna et al., 2020); barley (Adler et al., 2015; Spatari et al., 2020); and wheat (Adler et al., 2015).

5) DNDC: DeNitrification-DeComposition Model

The DeNitrification-DeComposition (DNDC) model is also process-based and models carbon and nitrogen fluxes in agro-ecosystems (IPBES, 2019; Li, n.d.; University of New Hampshire, n.d.). Originally developed in the 1990s for use in understanding processes in American agricultural soils, the model has expanded to include a variety of geographies, crops, soil types, and ecosystems (IPBES, 2019). Furthermore, the model can be used for simulating soil properties, agricultural management, effects of climate change, and more (Li, 1996). The DNDC model was used to estimate soil carbon flux in the literature for wheat in England (Ni et al., 2019), wheat in the USA (Antle et al., 2019; Tabatabaie et al., 2018b), corn in the USA (Tabatabie et al., 2018b), soybeans in the USA (Tabatabie et al., 2018b), and camelina in the USA (Tabatabie et al., 2018a).

6) EPIC: Environmental Policy Integrated Climate Model

The Environmental Policy Integrated Climate (EPIC) model, is also process-based and was developed at Texas A&M University to evaluate the effect of soil erosion on soil productivity as part of the application of the US *Soil and Water Resources Conservation Act* (Texas A&M AgriLife Research, n.d.). Since its creation, it has been modified to model a range of terrestrial ecosystems, their settings, and uses, including processes such as nutrient cycling and more (Izaurralde et al., 2012). The model has expansive use, particularly in agriculture where activities such as silage, yield, and leaching can be simulated (Izaurralde et al., 2006). Further, the model simulates SOC levels and hence flux to the atmosphere through climate-soil-management interactions (Causarano et al., 2008). The literature review identified eight instances of the EPIC model being used to simulate soil organic carbon flux. This includes modelling corn in the USA (Cronin et al., 2017; Kim et al., 2018; Lee et al., 2020a; Lee et al., 2020b; Sharara et al., 2020), soybeans in the USA (Cronin et al., 2017; Romeiko et al., 2020), rapeseed in the USA

(Ankathi et al., 2019), and canola in the USA (Ukaew et al., 2016). In these studies, the land management practices that were simulated include crop protection, crop rotation, irrigation, fertilizer, land use change, machinery use, residues, and tillage.

7) GHGenius

Originally developed for Natural Resources Canada (Life Cycle Associates, n.d.), GHGenius is a spreadsheet-based model used to calculate greenhouse gas emissions associated with transportation fuel pathways (Natural Resources Canada, 2016; GHGenius, n.d.; Life Cycle Associates, n.d.). Simulating the past, present, and future, GHGenius is a well-to-wheel model of conventional and alternative fuels (Natural Resources Canada, 2016; Life Cycle Associates, n.d.). Unlike other approaches described above, GHGenius is an empirical based model, which means that it is "based on correlations obtained from analysis of experimental data" (Ashoor et al., 2019). Amongst the literature reviewed, it was employed twice, once each to simulate corn grown in the USA (Obnamia et al., 2019), and camelina in the USA (Dangol et al., 2015). Land management practices that were simulated with GHGenius in the literature review are cover crops, irrigation, fertilizer, land use change, and tillage.

8) GREET: Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model

GREET, an acronym for the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies model, is a tool developed by the Argonne National Laboratory that models the full life cycle emissions and energy use of various fuel systems (Urgun-Demirtas, 2019; Argonne National Laboratory, 2020). GREET quantifies the life cycle Global Warming Potential (GWP) for the three major GHG emissions (CO_2, CH_4 and N_2O) (Life Cycle Associates, n.d.). The model is process-based and was used a total of three times throughout the literature review to assess soil organic carbon. The model simulated cover crops, crop protection, fertilizer, land use change, and tillage in terms of land management practices. The GREET model was used to simulate corn in the USA (Emery and Mosier, 2012; Obnamia et al., 2019), canola in the USA (Sieverding et al., 2016) and camelina in the USA (Sieverding et al., 2016).

9) SWAT: Soil and Water Assessment Tool

The Soil and Water Assessment Tool, SWAT, is a process-based model that was developed in partnership with Texas A&M university and the United States Department of Agriculture (Texas A&M, 2022). Developed to quantify the impact of land management practices in watersheds, the tool can be used to simulate crop growth, surface runoff, weather, pesticide loading, and a variety of other features and their effect on environmental impact (FAO, 2022; Texas A&M, 2022). It was only used once throughout the literature reviewed: simulating corn, soybean, and oat in the USA (Eranki et al., 2019). Land management practices that were simulated in this study include use of cover crops, crop protection, crop rotation, fertilizer, and machinery use.

10) Yasso07

The Yasso07 soil carbon model is the second iteration of the Yasso model developed by the Finnish Meteorological Institute (Finnish Meteorological Institute, n.d.). The empirical model "calculates changes in the amount of soil organic carbon and heterotrophic soil respiration" (Finnish Meteorological Institute, n.d.). Current uses of the model include greenhouse gas inventories, earth system modelling, and climate simulations, among others (Finnish Meteorological Institute, n.d.). In the literature reviewed, Yasso07 was identified once for its use in calculating soil organic carbon flux in a Finnish wheat system (Joensuu et al., 2021). The land management practices that were simulated with this approach are cover crops and land use change.

2.4.4 Organic vs. Conventional SOC Simulation

In choosing an approach to assess soil organic carbon flux, distinct management practices that align with one or another production mode (i.e., conventional, organic, etc.) potentially play an important role due to the underlying assumptions in the model and data which informs the model are incorporated. Hence, a review of the studies which model organic production may provide insight into the challenges or specification that may exist for modelling unconventional production practices (Table 2).

Table 2. Overview of studies identified through the literature review that estimated soil organic carbon flux in organic and/or non-conventional practices. Analysis includes which modelling method was used to assess SOC flux with each study,

land management practices that were simulated with each approach, and factors such as crops assessed and region.

Production Type	Crop	Region	SOC Quantification Method	Land Management Practices Simulated	Source
Ecological management	Winter wheat	Spain	Simple C model (other)	Crop rotation; Machinery use	González-García et al. (2021)
Mixed and organic	Alfalfa; Corn; Legumes	Italy	Sampling	Manure; Tillage	Gislon et al. (2020)
Organic	Alfalfa; Corn; Oat; Soybean; Wheat	Wisconsin	Sampling	Crop rotation; Crop protection; Fertilizer	Liang et al. (2017)
Organic	Wheat	Italy	Simple C model (other)	Crop protection; Fertilizer; Manure; Tillage	Chiriacò et al. (2017)
Organic	Lentil; Potato	Washington	Downloadable Software (CropSyst)	Crop protection; Fertilizer; Irrigation; Machinery Use; Tillage	Adewale et al. (2016)
Organic	Potato	Washington	Downloadable Software (CropSyst)	Crop rotation; Crop protection; Fertilizer; Machinery Use; Tillage	Zaher et al. (2016)
Organic	Rapeseed; Wheat	England	Simple C model (other)	Fertilizer; Machinery use	Brandão et al. (2010)

Of the 121 studies reviewed, only seven assessed potential changes in soil organic carbon in non-conventional production systems (Table 2). Among those seven, a variety of crops, regions, and land management practices were simulated. The most common method for assessing organic systems was use of a simple C model (n=3) in the form of a calculation or series of calculations (Table 2). The other two methods employed included sampling (n=2) and use of one of the downloadable software packages, CropSyst (n=2).

CropSyst was the only downloadable software package used in the simulation of SOC fluxes for organic production systems amongst the reviewed studies.

2.5 Discussion

2.5.1 Modelling Approaches for SOC in the LCA Context

A systematic review of the literature pertaining to LCA field crop studies which assessed soil organic carbon between 2010 and 2022 unveiled 121 papers which met the search criteria and revealed a surprising number and diversity of methods used to estimate SOC. This extraordinary number of methods reveals a complete lack of consensus within the LCA community about how to address this fundamental issue.

In total, 21 different methods were used to estimate SOC flux in mid-latitudinal field crop systems in conjunction with LCA studies. Ten studies used field sampling and laboratory measurements to quantify changes in SOC associated with different field crop production under different management practices. This approach is robust (subject to representativeness of samples taken, etc.), site-specific, and effectively accounts for all agricultural management practices and specificities of local conditions simultaneously. However, sampling can be costly, time consuming and sites must be sampled over two or more years, and may be unfeasible for large-scoped studies. If a research project has the means to sample, and it is within the scope of the study, sampling would provide an accurate representation of SOC change under real-world management and climate conditions. Where sampling is not feasible, a downloadable software package may be the next, most robust choice.

Amongst the 121 studies reviewed, 42 used one of 10 different downloadable software packages to model soil organic carbon in LCA field crop studies. Some of these software packages were built for estimating SOC fluxes specifically amongst other aspects of farm performance (i.e., Yasso07, etc.) while others were not specifically designed for modelling SOC, but researchers use underlying data and emissions factors embedded in the software to estimate SOC in soils and hence potential changes in SOC nonetheless (or in the case of GHGenius and GREET, using transport fuel models and empirical data). Using these downloadable software can be more time consuming than a simple C model, but many software packages available integrate location specific soil and historic climate data, and incorporate provisions for modelling the effect of a range of agricultural management practices: making them more site specific and sensitive to specific management practices than a simple C model. However, the sizeable number of software packages makes choosing an appropriate one difficult. Moreover, the variety of these software that appear in the literature means that LCA study results, even if the same agricultural practices are used to grow a given crop in a specific location, may not be directly comparable due to potential differences in the software package inputs, calculations and assumptions. This challenge of methodological heterogeneity resulting in potentially inconsistent results is not unfamiliar in LCA studies more generally but it does point to the importance for an LCA-specific methodology for assessing SOC flux in soils. Nevertheless, downloadable software packages are a practical alternative to sampling and may be more accurate and generalizable than a simple C model. However, where a downloadable software or sampling will not work for every study, a simple C model may be the best choice for integration with some LCA studies.

Given their availability and general application it is then not surprising that amongst the 121 studies reviewed, 69 employed one or another simple soil C calculation technique that used one or more equations. This technique also included calculations that were adopted from previous studies, IPCC guidelines, emission factors and estimations, and other readily available calculations. Not only are these techniques readily available, often fairly simple to apply but are often provided by generally reputable organizations (i.e., from government and international sources). These characteristics make them an accessible and attractive choice for including SOC fluxes in LCA studies. However, like the downloadable software, there are a vast number of simple C models, and each have their limitations in accurately depicting soil interactions. For example, emissions factors are regionalized numbers which may not be representative of the exact study site and conditions of the agricultural management. Therefore, if modelling SOC fluxes with LCA, one may want to consider sampling or using a downloadable software tool to account for various LMP and agro-climatic conditions. If neither of these options are feasible for the study, then a simple C model would be appropriate to include.

2.5.2 Modelling Approaches for SOC: Accounting for Land Management Practices

Direct sampling and testing of soils over time to estimate SOC changes is not only more accurate but functionally integrates real-world site characteristics (i.e., climate, weather, etc.), but also actual land management practices. Sampling allows for any and all land management practices to be captured or reflected in full in results. However, the specific influence of individual site characteristics or management practices employed on actual SOC flux observed cannot be readily disentangled without potentially elaborate experimental set up (e.g., a series of parallel plots, with replicates, that vary in terms of individual management interventions, all sampled and tested over a number of years), nor are the results readily generalizable. Moreover, the sampling approach is costly and unfeasible for many studies. Therefore, sampling may be appropriate for well supported, small-scale studies within a limited geographic scope.

Where research resources are more limited, potential geographic scope is large, or farmer participants are not recruited sufficiently early to permit ‘before’ sampling, using downloadable software to model SOC in association with land management practices may be an effective choice. Many downloadable software packages are constantly improving and updating to incorporate new features, including calculations that accommodate a variety of LMP. This means that the potential effects of individual management interventions on sites can be modeled relatively quickly by the simple addition or subtraction of specific inputs and estimated changes in yield etc. While the analysis in Section 2.4.2 does not reflect the management interventions that available models are currently capable of simulating, most of the software packages that emerged in the reviewed studies have the ability to simulate all of the land management practices analyzed (cover crops, crop protection, crop rotation, irrigation, fertilizer, land use change, machinery use, manure, residues, and tillage) and more.

2.5.3 Modelling Approaches for SOC in the Organic Context

There is not an organic management-specific downloadable software package available to the authors' knowledge. However, the flexibility of all downloadable models' ability to simulate a variety of LMP makes incorporating organic practices easier. Moreover, several downloadable models such as CropSyst, and EPIC, have been built to simulate differences in the composition of a range of both organic and inorganic fertilizers. Therefore, the choice of modelling approach may be system dependent: subject to fertilizers used, land management practices implemented, geography, etc.

2.5.4 Limitations

Many limitations of this study surround the use of Scopus, its functions, and choosing the best search terms. As previously described in the methods, several exclusionary criteria were used to limit the scope of the search to a reasonable number of papers (i.e., discipline, language, paper type, and geography). Papers which potentially fit the search criteria could have been unintentionally ignored because they were (i) not labeled or incorrectly labeled with geography, (ii) not labeled or incorrectly labeled with field of study (i.e., agriculture, environmental science, etc., or (iii) not labeled or incorrectly labeled with paper type (i.e., article, conference paper, etc.), thus excluding them from the final search results. To remain within a manageable scope of papers to assess, these exclusionary criteria were unavoidable, hence the potential for missed papers. Additionally, the vast number of available SOC estimation approaches and limited guidance for their incorporation alongside LCA mean that viable SOC modelling tools may not have been captured with this literature review. For example, Holos, a Canadian-specific whole-farm greenhouse gas emissions accounting tool developed by Agriculture and Agri-Food Canada used to model and test on-farm emissions reduction methods (Agriculture and Agri-food Canada, 2022a; NDC Partnership, n.d), was not used as a SOC estimation approach in this review. However, Holos has the ability the simulate all identified LMP and both inorganic and organic fertilizers.

2.6 Conclusion

Soil organic carbon is an important aspect of agricultural soils that can affect production in a number of ways. Moreover, changes in SOC levels can play an important part in either mitigating or increasing GHG emissions from agricultural production. Despite the important role that SOC flux can play in understanding the net GHG emissions that arise from agriculture, it has historically been absent from most life cycle assessment studies of these systems. Its absence from many agricultural LCAs appears to largely reflect a lack of clear, well-established procedures for quantifying SOC flux in the context within which many LCA are conducted. When it has been included in LCA studies, there is a lack of consensus on modelling approaches. A literature review of 121 LCA field crop papers revealed 21 different approaches to modelling soil organic carbon fluxes in mid-latitudinal agricultural systems growing field crops. These approaches ranged from repeated sampling, to the use of downloadable software packages that may or may not be tuned to local soil and climate conditions, to simple C models. This enormous range of approaches echo the findings of Goglio et al. (2015): that the LCA community needs clarity on tackling SOC flux in life cycle assessment studies.

When it comes to choosing a modelling approach, a researcher should apply an individualistic lens to their decision, depending on the research they are trying to perform. It should be dependent on system type (i.e., organic, conventional, etc.), land management practices, geographic scope, willingness of uncertainty, time constraints, and budgetary constraints. Whatever method, it is imperative that SOC flux are included in LCA studies moving forward. The inclusion of SOC will help create a holistic picture of agricultural systems and identify the potential role they may play in mitigating against climate change.

Future research should focus on expanding the literature review geography to include an assessment of globally used models. Further, future research should explore a comparison of each of the identified models to analyze accuracy of these models with a variety of crop types, management practices, and geographies. This holistic model comparison could shed light on an overall, best performing model.

CHAPTER 3: LIFE CYCLE ASSESSMENT OF WESTERN CANADIAN ORGANIC OATS, RYE, AND WHEAT

3.1 Introduction

The Canadian Prairies are an agricultural powerhouse for field crops: 86% of the total field crop area in Canada occurs in the Prairie provinces of Alberta, Manitoba, and Saskatchewan (Statistics Canada, 2017). Fully 85% of the nation's rye production (Statistics Canada, 2008), 90% of the nation's oat production (Canadian Grain Commission, 2019b) and nearly 95% of the nation's wheat production (Liu and Lobb, 2021; Statistics Canada, 2017) occur in these three Prairie provinces. Most of this production is conventional, and the practices used to produce these crops result in substantial environmental and resource degradation impacts such as greenhouse gas emissions (Awada et al., 2021), use of non-renewable energy inputs (Hoeppner et al., 2007; International Institute for Sustainable Development, 1994), biodiversity loss (Thiessen Martens et al., 2015), soil degradation (Agriculture and Agri-food Canada, 2010), and water quality degradation (Agriculture and Agri-food Canada, 2010; Lui and Lobb, 2021), among other concerns.

However, organic demand and production in Canada are growing quickly. The Canadian organic industry is the sixth-largest organic industry in the world, valued at $8 billion (Agriculture and Agri-Food Canada, 2021b). Demand for organic food is increasing by 8.7% annually, but Canadian suppliers cannot keep up (Agriculture and Agri-Food Canada, 2021b). In terms of organic field crop production, the Prairies account for ~81% of the nation's total field crop area in organic production, with 94,535 ha in production in Alberta, 222,540 ha being organically farmed in Saskatchewan, and 22,740 ha in production in Manitoba as of 2017 (Canada Organic Trade Association, 2018). The Prairies are responsible for 93% of organic oat production, 66% of organic rye production, and 93% of organic wheat production nationally (Canada Organic Trade Association, 2019).

Despite its scale, relatively little is known about the resource depletion and environmental performance of Canadian organic field crop production systems. Much of our current understanding of agriculture's contributions to regional- to global-scale resource and environmental degradation (e.g., climate change, eutrophication, etc.) is a result of the application of life cycle assessment (LCA) to these important human activities (Meier et al., 2015; Poore and Nemecek, 2018, van der Wert et al., 2020). LCA is a framework used to quantify material and energy inputs and outputs (e.g., emissions, waste) associated with providing a good or service throughout its life cycle (ISO, 2016a; ISO 2016b), and then calculating the resulting impacts. The LCA methodology is frequently used to assess agricultural systems because environmental impacts can be compared between management practices, cropping systems, and other variables (Haas et al., 2000). In Canada, LCA has been used to characterize global warming potential (GWP), along with a number of other impact categories, of a range of agricultural systems such as conventional and organic apple production in Atlantic Canada (Keyes et al., 2015), conventional beef production in Western Canada (Beauchemin et al., 2010), conventional camelina production in Western Canada (Li and Mupondwa, 2014), and conventional experimental field crop production in Alberta (Goglio et al. 2014), along with organic Canadian canola, corn, soy and wheat production (Pelletier et al. 2008). Nevertheless, there are few LCA studies of Canadian organic field crop production, particularly given the scale of organic oats, rye, and wheat production in western Canada.

Given the rapid growth of organic farming in Canada, and in particular the scale of cereal crop production in western Canada, it is important to understand how contemporary Canadian organic farming practices contribute to climate change, along with a set of additional resource depletion and environmental concerns, using the best available data and assessment techniques. LCA studies of organic production in other regions (for example Kokare et al., 2014; Przystalski et al., 2008; Reid et al., 2011; among others) show that the relative life cycle performance of organic vs. conventional farming varies between crop, specific management practices, geography, and other variables. For example, a study by Venkat (2012) found that organic systems had higher GHG emissions than conventional systems in 7 out of 12 crop systems. Furthermore, a comparison study by Cavigelli and colleagues (2008) found that organic yields in field crop rotations were as much as 41% lower than those of conventional yields.

A review of 16 recent (2010-August 2022) LCA studies focused on organic oats, rye and wheat production around the globe provides insights into methodological and organic farming issues (full details of papers reviewed found in Appendix B). Organic nutrient amendments, such as manure, were often identified as the main contributors to impact categories such as global warming potential (Jeswani et al., 2018; Zingale et al., 2022), acidification, eutrophication, photochemical oxidation (Zingale et al., 2022), energy use (Hoffman et al., 2018) and terrestrial ecotoxicity (Viana et al., 2022) due to the application, sourcing, and transportation of nutrient amendments. Field emissions due to nutrient inputs were also identified as a major source of emissions contributing to global warming potential (Carranza-Gallego et al., 2018; Chiriacò et al. 2017; Rebolledo-Leiva et al., 2022), stratospheric ozone depletion, terrestrial acidification, freshwater eutrophication, and marine eutrophication (Rebolledo-Leiva et al., 2022). Importantly, a majority of soil emissions were most often associated with manure application. Several studies also identified machinery use as a large contributor to global warming potential emissions (Chiriacò et al., 2012; Hoffman et al., 2018; Huerta et al., 2012; Jeswani et al., 2018; Moudrỳ Jr. et al., 2013a; Moudrỳ Jr. et al., 2018).

Representative data collection for agricultural LCA is always a challenge, and approaches for collecting data for the foreground processes varied between the 16 studies. Eight of the studies used a field experimentation method to gather life cycle inventory data (Carranza-Gallego et al., 2019; Cibelli et al; 2021; González-García et al., 2021; Huerta et al., 2012; Hoffman et al., 2018; Miksa et al., 2020; Moudrỳ Jr. et al., 2018; Rebolledo-Leiva et al., 2022) (i.e., the study conducted an experiment by growing crops and gathered data on the study plot under a specific and monitored set of conditions). Another seven studies used surveys/questionnaires or interviews to collect life cycle inventory data, but with a relatively small number (<5) of surveys/questionnaires and interviews used to characterize an equally small number (<5) of plots, farms, or rotations (Bhattacharyya et al., 2019; Chiriacò et al., 2017; Jeswani et al., 2018; Moudrỳ Jr. et al., 2013a; Moudrỳ Jr. et al., 2013b; Viana et al., 2022; Zingale et al., 2022). One study relied only on secondary data (Tuomisto et al., 2012). Since agricultural LCA studies have identified that environmental performance is affected by the type of crop, management practices, agroclimatic conditions, the small number of data points makes it difficult to characterize and understand these drivers of organic production impacts.

The potential role that changes in soil organic carbon (SOC) can play in net GHG emissions of many farming systems is of increasing importance (Crippa et al. 2021, Kimble et al., 2016; Lal et al., 2007; Zomer et al., 2017). In particular, organic farming is increasingly being offered as a solution to mitigate climate change through SOC sequestration. In general, relatively few agricultural LCA studies have incorporated SOC dynamics into the quantification of life cycle GHG emissions (Goglio et al. 2014). Of the more recent studies on oats, wheat, and rye, only four accounted for SOC changes to some extent (i.e., Carranza-Gallego et al., 2019; González-García et al., 2012; Huerta et al., 2012; Rebolledo-Leiva et al., 2022). These studies used a variety of methods ranging from applying: a simple carbon credit from the application of compost which captures and offsets emissions from farm inputs (Huerta et al., 2012); the Humified Soil Organic

Carbon Model (Carranza-Gallego et al., 2019); and a seven-step biophysical model (González-García et al., 2021; Rebolledo-Leiva et al., 2022).

There are only two LCA studies of organic field crop production in Canada that provide some insights into potential concerns. The earliest Canadian study by Pelletier and colleagues (2008), characterized potential life cycle global warming potential, ozone depleting, and acidifying impacts, along with cumulative energy demand associated with Canadian organic and conventional canola, corn, soy, and wheat production, and found that impact contributions associated with these organic crops were an average of 61% lower than those for conventional farming across the four impact categories considered (Pelletier et al. 2008). However, this study drew entirely on Canadian census data and other published values to build life cycle inventories instead of using primary sources. The more recent study by Viana and colleagues (2022) assessed the environmental impacts of organic and conventional oat grains in Eastern Canada through LCA. The study used primary data from one study farm to conclude that environmental benefits are highly dependent on geographic-, farmer-, and practice-specific context. (Viana et al., 2022). The study also concluded that shifting oat production from conventional to organic would not result in decreases in environmental impacts in the study context. (Viana et al., 2022)

It is evident that there is a lack of LCA research of Canadian field crop production under organic management, and in particular research using primary data derived from a large number of working organic farms, so as to better characterize the role of management practices, nutrient amendments, and agroclimatic conditions on impacts. More importantly, relatively few studies of organic field crop systems have attempted to quantify SOC changes on organic farming systems as part of the life cycle inventory of organic production. Therefore, this study addresses the following research questions:

1) What are the net life cycle environmental impacts of Canadian Prairie oat, rye, and wheat cropping systems, specifically climate change (long term), fossil and nuclear energy use, freshwater acidification, freshwater ecotoxicity, freshwater eutrophication, and land occupation?
2) What are the implications of soil organic carbon changes to total climate change impacts?

3.2 Methodology

Life cycle assessment was used to evaluate contributions to the life cycle GHG emissions and other impact categories selected that arise from the production of wheat, oats, and rye under organic management in Alberta, Manitoba, and Saskatchewan. 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.

3.2.1 Goal and Scope Definition

The goal of this analysis is to quantify and compare the cradle-to-harvest gate net contributions to impact categories that result from organic wheat, oats, and rye production in the Western Canadian provinces of Alberta, Manitoba, and Saskatchewan.

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.

3.2.1.1 Product System Description

The crops studied were wheat, oats, and rye in the Western Canadian provinces of Alberta, Manitoba, and Saskatchewan. 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, oats, and rye). This study does not represent each variety or class of wheat, oats, or rye. 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, oats, and rye in Western Canada. Instead, this study represents a smaller sample of potential average Western Canadian wheat, oats, and rye crop production systems.

3.2.1.2 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 FU is one metric tonne wet harvested crop, referred to as "1 t", or "1 t Canadian organic field crop harvested". In this analysis, it is assumed that at harvest, all oats have a moisture content of 13.6%, rye of 14.1%, and wheat of 14.6% (Canadian Grain Commission, 2019).

3.2.1.3 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 Western Canadian wheat, oats, and rye 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.

3.2.1.4 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 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 allocation process (Curran, 2015; ISO, 2016b). The co-products in the system were biologically fixed nitrogen from 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 (i.e., allocated based on physical characteristics such as available nitrogen).

Importantly, other pulse crops that could biologically fix nitrogen as a co-product (e.g., peas, lentils, etc.) only appeared as green manures.

Manure was assumed to be a co-product of conventional livestock production, and was treated as a recycled product. This assumption is based on the research which shows that organic farms receive most of their nutrients by way of conventional farms, mostly through manure (Nowak et al, 2013). 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).

3.2.1.5 Data Quality Requirements

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

1) Spatial
2) Temporal
3) Technological

This study provides a snapshot of cradle-to-harvest gate field crop production emissions across Western Canada. 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. 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) is also considered when calculating field-level emissions, such as soil carbon changes. This is because land management history is an input to the soil organic carbon modelling.

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 Western Canadian organic field crop production systems in accordance with LCI data gathered from survey participants regarding their management practices, discussed in the section below.

3.2.1.6 Impact Assessment Method and Category

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, freshwater ecotoxicity, and land occupation and biodiversity. The corresponding midpoint level characterization units are kg $CO_{2\ eq(long)}$/kg , MJ deprived/kg dissipated, kg $SO_{2\ eq}$/ kg emitted, kg PO_4 P-lim eq/ kg emitted, PAF m^3 day/kg, m^2 arable land eq ⋅yr/(m^2occupied ⋅ yr), respectively (Bulle et al., 2019).

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

In IMPACTWorld+, the climate change characterization factor refers to the radiative forcing of a greenhouse gas relative to the radiative forcing of carbon dioxide (Bamber et al., 2020; 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 greenhouse gas 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., 2020), 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.

Expressed as CTUe (comparative toxic unit equivalents), freshwater ecotoxicity indicates damages to ecosystem quality from chemical emissions (LC-Impact, 2019). IMPACTWorld+ uses a parameterized version of USEtox to measure ecotoxicity impacts (Bulles et al., 2019). The indicator used to quantify this impact is toxicity impacts: an "estimation of the potentially affected fraction of the exposed ecosystem species integrated over time and water volume per unit mass of a chemical emitted" (Bamber et al., 2020, p 83).

The land occupation category measures the effect of land occupation on biodiversity loss over a given period of time (Bamber et al., 2020). 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).

3.2.1.7 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 excluded include 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.

3.2.2 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 4.

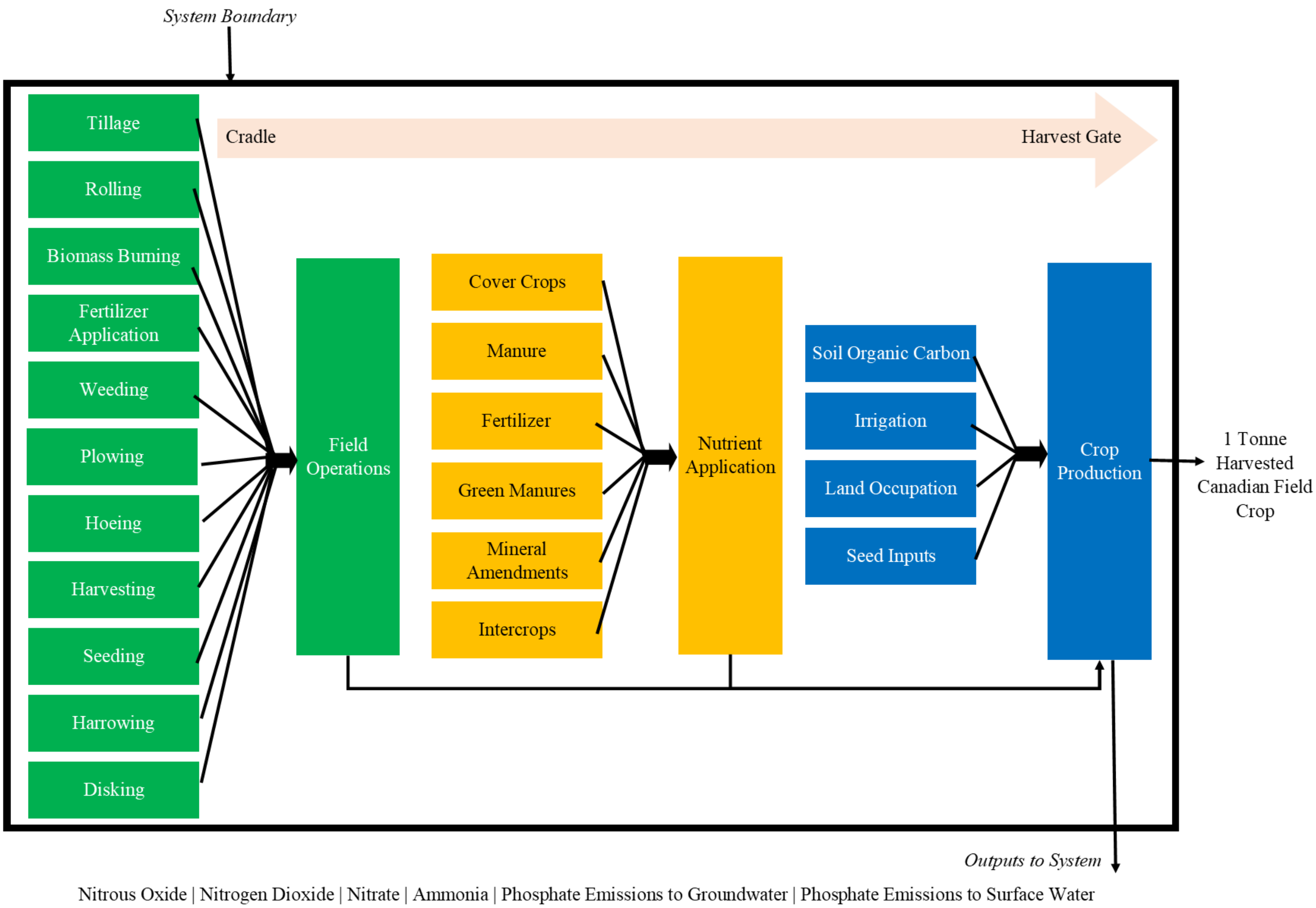

Figure 4. System boundaries for modeling Western Canadian organic wheat, oats, and rye production

3.2.2.1 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 C). The producers who were surveyed met the following criteria:

- 18 years of age or older
- 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 greenhouse gas 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). Complete details regarding participant recruitment methodology and retention are found in Appendix D.

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).

Results in this analysis reported on organic wheat, oats, and rye include data from 16 farms across Alberta, Manitoba and Saskatchewan totaling 27 farm-crop combinations (Table 3). The approximate geographic location of farms that provided data is shown in Figure 5. 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 5 correlates with the production of wheat, oats, and rye production in the growing regions of Alberta, Manitoba and Saskatchewan.

Table 3. Breakdown of farm-crop combinations by province

Province	Crop(s)	Number of Farm-Crop Combinations
Alberta	Wheat	2
	Oats	2
	Rye	1
Manitoba	Wheat	1
	Oats	0
	Rye	1
Saskatchewan	Wheat	9
	Oats	8
	Rye	3

Prior to modeling, all data were reviewed for completeness and seeming outlier data. Where concerns were identified, farmers were re-contacted for clarification. In

Figure 5. Approximate locations of Prairie farms that provided data for this analysis. Red clusters indicate a grouping of three or more farms to maintain producer anonymity. Farm locations are overlaid on a map from the American Birding Association (n.d.).

addition, to ensure yields reported were reasonable they were compared against the 2021-2022 averages of wheat, oats, and rye yields from Western 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).

3.2.2.2 Background Data

The life cycle database, ecoinvent version 3.8 (GreenDelta, 2022) 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 F. 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.A. 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 G).

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 Western 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 F for all modifications of processes drawn from ecoinvent v 3.8).

3.2.2.3 LCA Model Structure

The life cycle assessment modeling software openLCA 1.11 (2021) from GreenDelta was used to model and quantify impacts of wheat, oats, and rye grown under organic management in Western 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 6).

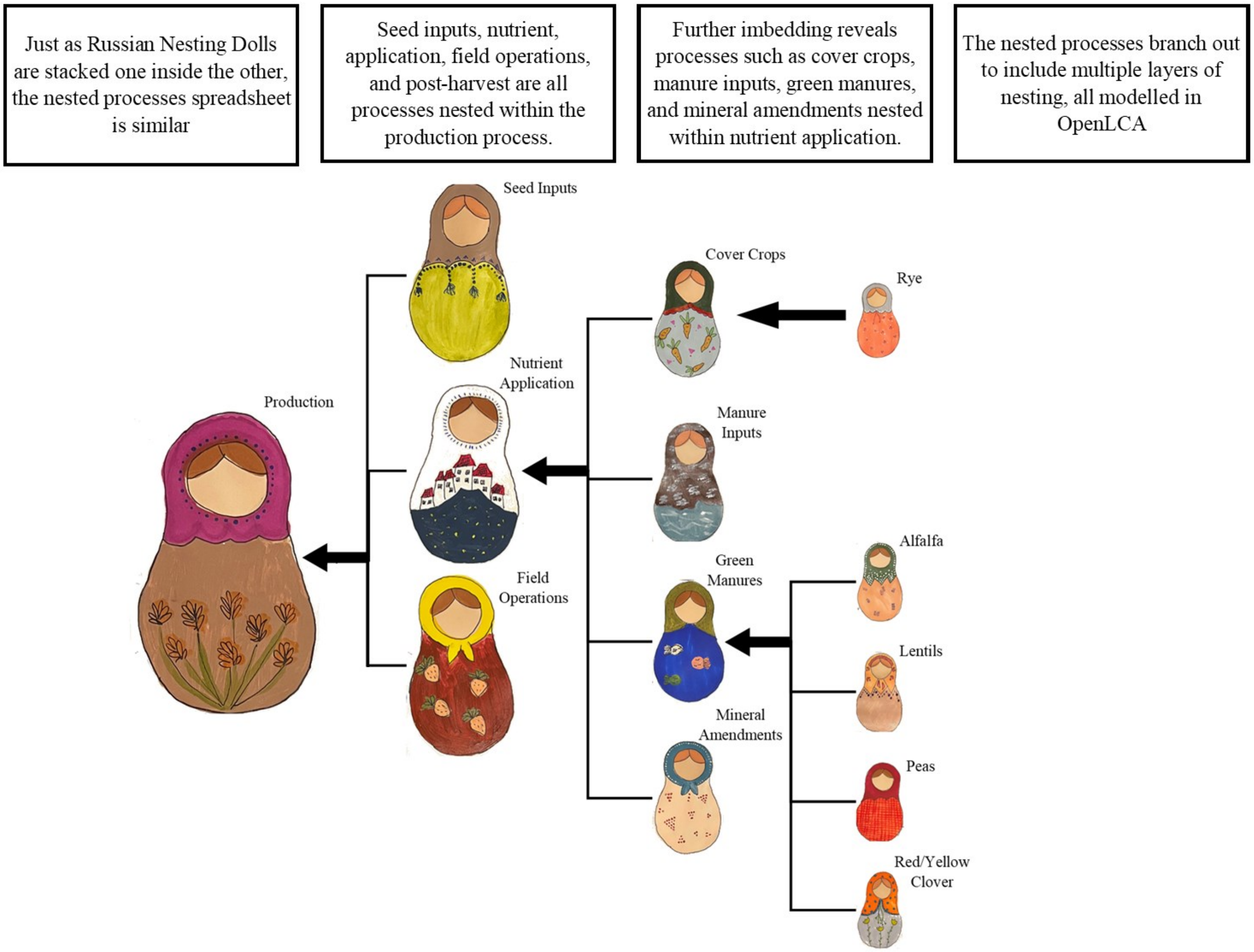

Figure 6. High-level overview and explanation of nested processes structure.

The following sections provide more details of how each nested process was modeled inside the production process (see Appendix H for details on the production process inputs):

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 I.

Seed Inputs: The life cycle inventory for seed production was obtained from ecoinvent. The seed inputs included: organic seeds for barley, fava bean, grass, maize, 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 J.

Nutrient Application: Nutrient applications (Appendix K) included manure (Appendix L), green manure (Appendix M), cover crops (Appendix N), and mineral amendments (Appendix O). 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.

3.2.2.3.1 Modelling Nutrient Inputs

3.2.2.3.1.1 Manure

In the farm inventory data provided by farmers, many specified that nutrients were supplied through animal manure (cattle, poultry, swine, and 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 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 (Kyttä 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 7). 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)

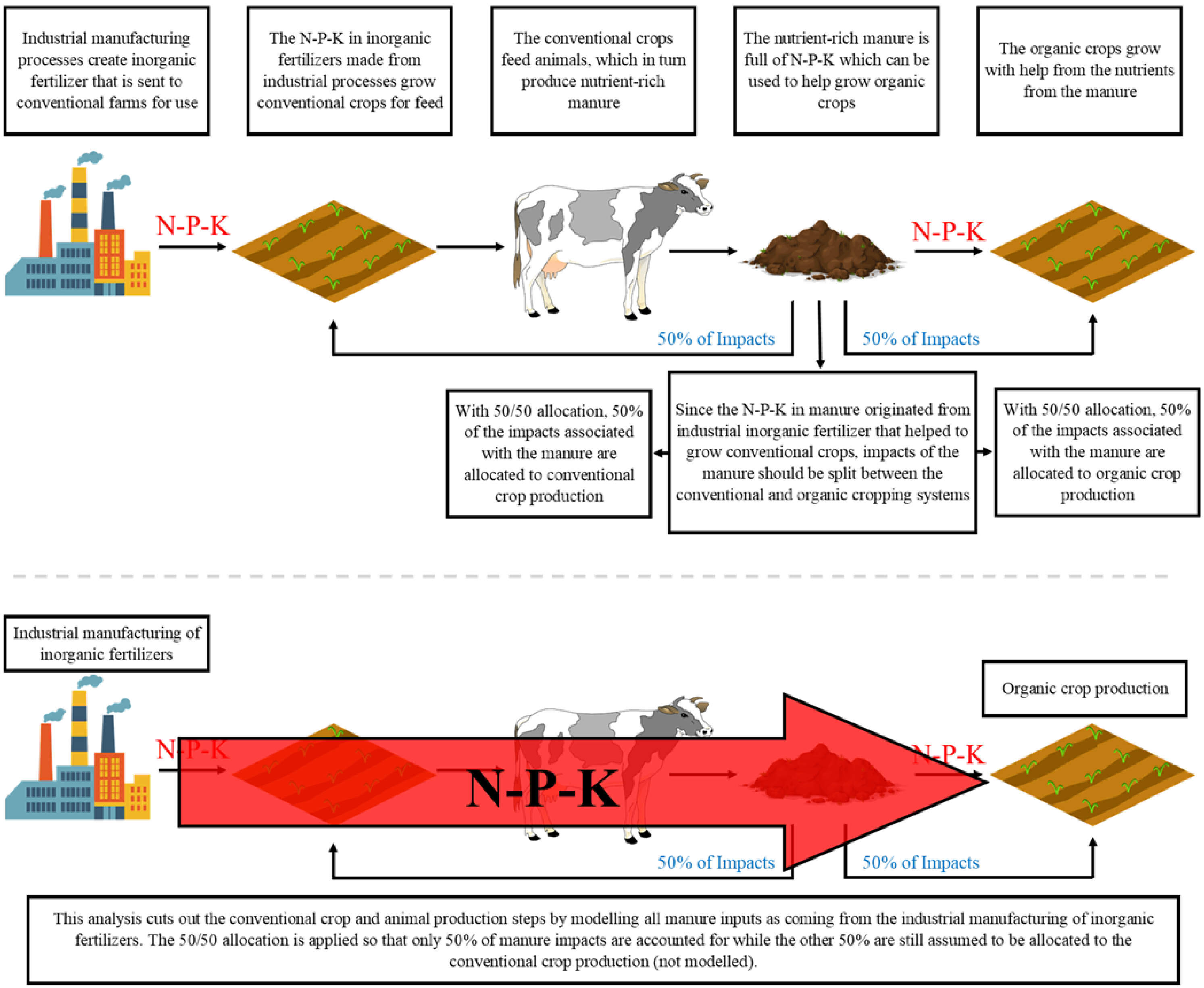

Figure 7. 50/50 allocation methodology demonstrating the proportion of upstream impacts from the production of inorganic N, P, and K assigned to the production of the conventional feed (50%) and the organic field crop (50%).

The types of fertilizers used to represent the nutrients in 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 Q. The processes and providers chosen from ecoinvent are shown in Appendix F.

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.

Manure inputs are often a large source of life cycle impacts in both conventional and organic agricultural systems, and as such, a potential candidate for testing the sensitivity of model outcomes based on changes in manure application. However, in this research manure was not considered as a potential concern for sensitivity analysis as manure inputs only occurred in 4 of the 27 farm crop inventories modeled and the volumes applied were small.

3.2.2.3.1.2 Green Manures (GMs) 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 or 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.

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, rye cover crops suppress weeds, 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 (Clark, 2015; Government of Ontario, 2016; Department of Agriculture; 2022; Kessavalou & Walters, 1999; Wayman et al., 2017). 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. Figure 8 illustrates the nitrogen allocation methodology with a mock crop rotation.

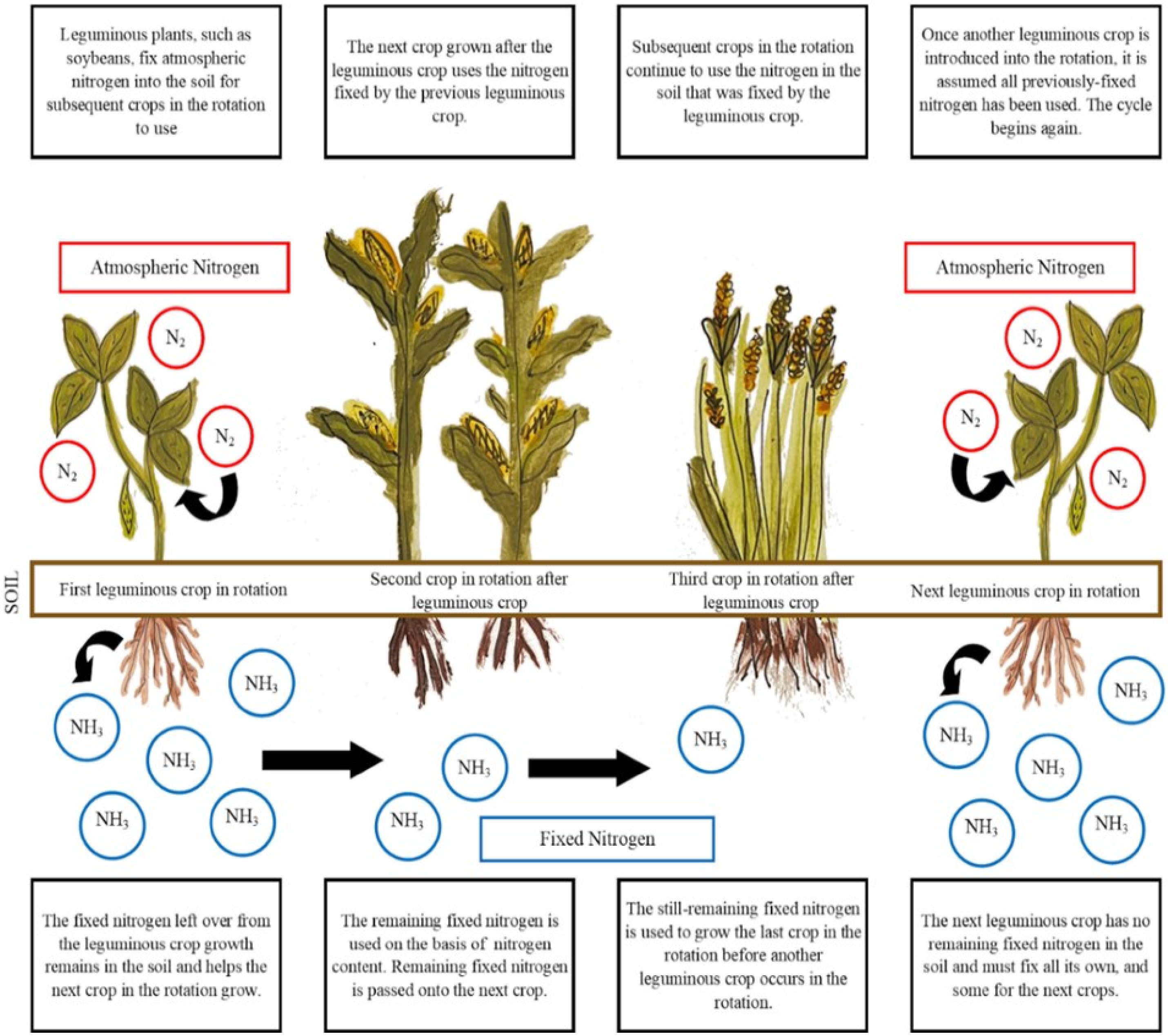

Figure 8. Allocation of nitrogen fixed by a leguminous crop is shown through a soybean-corn-wheat rotation.

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 9 and Appendix Q). 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 9. 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 (CCOF) (2022).

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

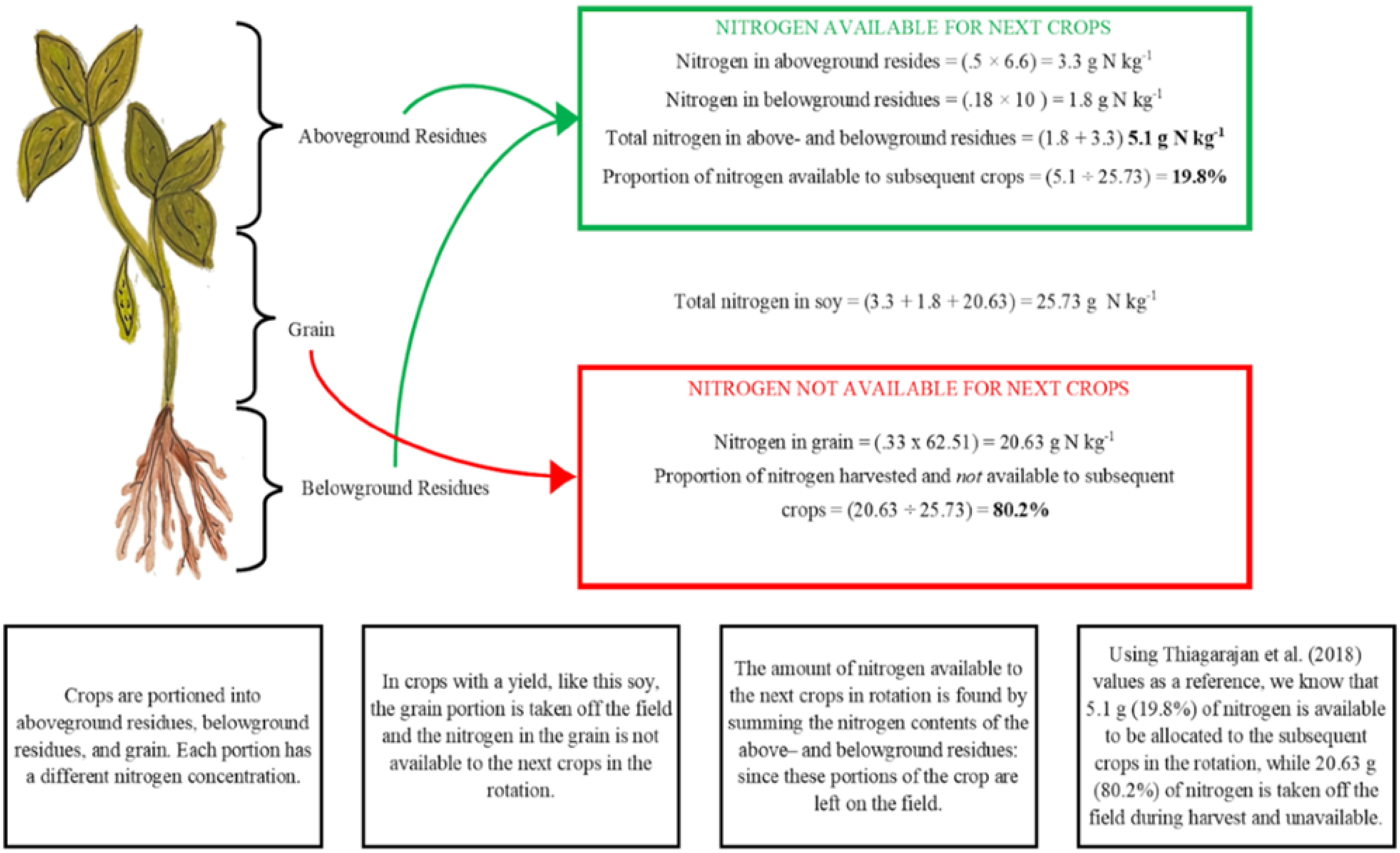

Figure 9. Two-step process of allocating soil emissions and life cycle environmental impacts resulting from leguminous crops where a harvest occurs between that crop and subsequent crops are grown in rotation.

Uncertainty arises from activity data such as green manures (GM), which are not only sources of nutrients but also of soil related emissions and impacts that arise from their cultivation. The assumption that green manure impacts were allocated to subsequent crops grown in rotation in proportion to the nitrogen content of those harvested crops has impacts on nitrogen emissions and subsequent life cycle impacts. The choice to allocate impacts of green manures to all subsequently grown crops in a rotation in proportion to the nitrogen contents of harvested crops could have dramatically affected the outcome impacts (see results in Section 3.3.2). 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 8), 100% of GM or leguminous crop impacts were placed solely on the succeeding crop in the sensitivity analysis. 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 GMs or leguminous crops with a yield. 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. Results of this sensitivity analysis are discussed in Section 3.3.3.1.

The LCI data used in this LCA study includes primary data provided by Canadian organic field crop farmers, published literature, government reports, databases, and LCI datasets. In general, the primary data collected from Canadian farmers were accurate, valid and 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. 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. As described above, LCI datasets were modified to best represent central Canadian production conditions. 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 a Western Canadian red clover crop is potentially inappropriate and perhaps misrepresents its true environmental impact. Using these limited LCI datasets as a representative of all GM production is associated with potentially high uncertainty, particularly in terms of how geographic setting might impact GM yield. Uncertainties concerning accurate representation of green manures in the Prairies 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 SOC modelling green manure yields. Results of this sensitivity analysis are discussed in Section 3.3.3.1.

3.2.2.3.2 Modelling 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 R. 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 10).

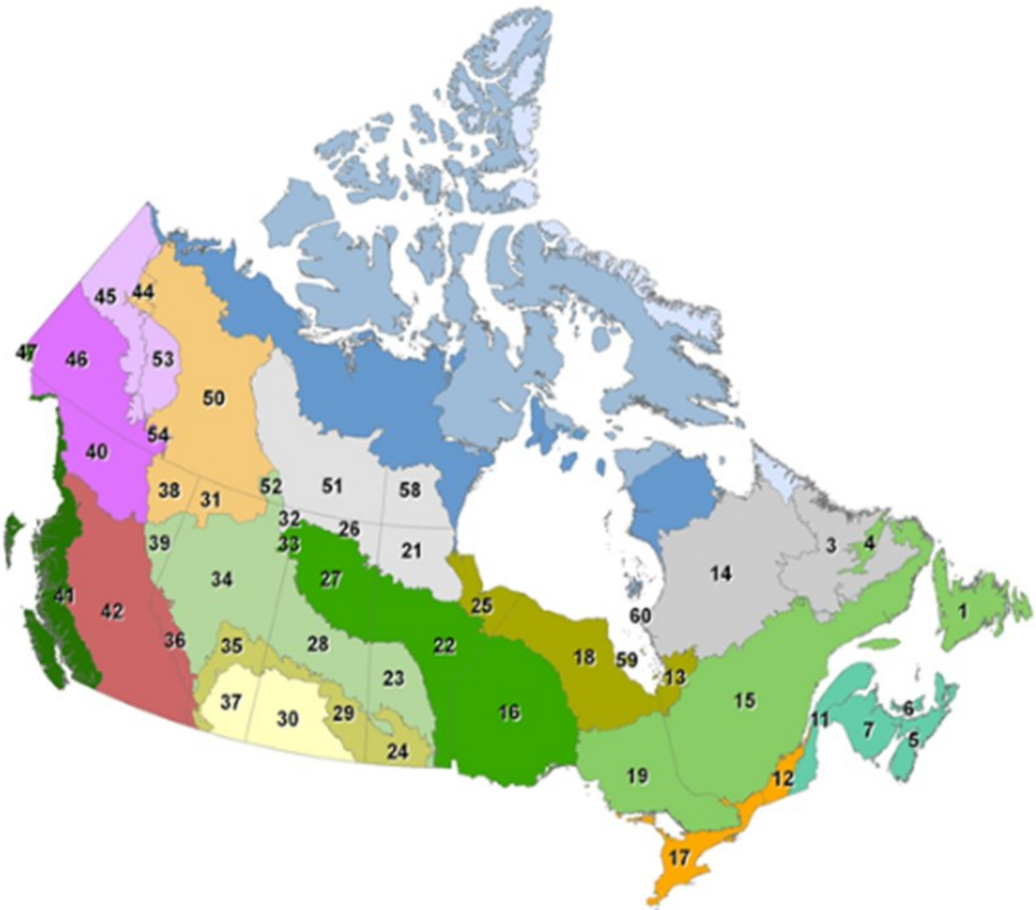

Figure 10. The reconciliation unit map of Canada created by Natural Resources Canada (2011) is used to "ensure consistency of data from multiple agencies during the development of estimates" and is the smallest unit for which results are calculated in this analysis

3.2.2.3.2.1 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:

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

Where

- N_2O-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 (i.e., mass of N_2O-N × (44÷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-N per kg N applied) (NIR Part 2, A6.4-20)
- $EF_2\ F_{cr}$ = emissions factor for crop residue nitrogen lost as N_2O following application to agricultural soils (kg N_2O-N per kg N applied) (NIR Part 2, A6.20)
- $EF_1\ F_{som}$ = 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) (NIR Part 2, A6.20)

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 with F_{on} are used as the emissions factors for F_{som} (i.e. EF_1F_{som}). Considering that F_{som} requires an emissions factor for Equation 1, the absence of published emissions factors for "F_{som}", and the definition of all emissions factors for direct N_2O, it was assumed that the emissions factors associated with F_{on} could be used as the soil organic matter (F_{som}) emissions factor.

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

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

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}) (as derived from crop inventories)
- $N_{Amendment1}$ = nitrogen content of amendment 1 (%)

- A_2 = amount of second manure or organic amendment applied to crop (kg N t^{-1}) (as derived from crop inventories)
- $N_{Amendment2}$ = nitrogen content of amendment 2 (%)
- A_x = additional amount of manures or organic amendments applied to crop (kg N t^{-1}) (as derived from crop inventories)
- $N_{AmendmentX}$ = nitrogen content of additional amendments applied to crop (%)

Representative nitrogen contents of manure and other nutrient sources were derived from numerous sources and can be found in Appendix S and T, 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 of the crop grown (if applicable) (kg N ha^{-1}) (derived from crop inventories)
- DM_G = typical grain dry matter fraction of the green manure crop being grown (%) (CCOF, 2015; Feedipedia, 2022)
- N_G = nitrogen content of the grain partitioning of the crop (g N kg^{-1}) (Thiagarajan et al. (2018); Janzen et al. (2003))
- N_{AGR} = nitrogen content of the aboveground residue partitioning of the green manure crop (g N kg^{-1}) (Thiagarajan et al. (2018); Janzen et al. (2003))

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

Since some leguminous crops that were grown in some rotations had their grain fraction harvested (e.g., soybeans), in calculating the nitrogen available to subsequent crops being grown in rotation it was important to exclude the grain portion of the leguminous plant. Therefore, to find the nitrogen content of leguminous crop residues when a harvest was taken off, Equation 1.2.1 was used (and illustrated in Figure 9):

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

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

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 other leguminous crop is grown was determined with Equation 1.3 (and as illustrated in Figure 8):

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

Where

- $F_{NFractionGM}$ = the fraction of 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 (and as illustrated in Figure 9):

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

Where

- $F_{NFractionL}$ = the fraction of 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 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 R). 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 9 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 = 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}) (Thiagarajan et al. (2018); Janzen et al. (2003))

- N_{BGR} = nitrogen content of the belowground residue partitioning of the crop (g N kg^{-1}) (Thiagarajan et al. (2018); Janzen et al. (2003))
- G_{DM} = calculated plant partitioning of total plant dry matter into grain (% of DM) (Thiagarajan et al. (2018); Janzen et al. (2003))
- AGR_{DM} = calculated plant partition of total plant dry matter into aboveground residue (% of DM) (Thiagarajan et al. (2018); Janzen et al. (2003))
- BGR_{DM} = calculated plant partition of total plant dry matter into belowground residue (% DM) (Thiagarajan et al. (2018); Janzen et al. (2003))

Sources for calculated plant partition 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 Appendix Q. Where 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:

- Tame hay (alfalfa & mix) values in place of clover,
- Wheat values in place of spelt,
- 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:

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} = nitrogen content of the aboveground residue partitioning of the crop (g N kg^{-1}) (Thiagarajan et al. (2018); Janzen et al. (2003))
- N_{BGR} = nitrogen content of the belowground residue partitioning of the crop (g N kg^{-1}) (Thiagarajan et al. (2018); Janzen et al. (2003))
- G_{DM} = calculated plant partitioning of total plant dry matter into grain (% of DM) (Thiagarajan et al. (2018); Janzen et al. (2003))
- AGR_{DM} = calculated plant partition of total plant dry matter into aboveground residue (% of DM) (Thiagarajan et al. (2018); Janzen et al. (2003))
- BGR_{DM} = calculated plant partition of total plant dry matter into belowground residue (% 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 of interest 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:

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

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:

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

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}) (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 that time.

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 1.8

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 Q)
- $AGR_{\%\ of\ DM}$ = 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 Q. 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,
- T. hay (alfalfa & mix) values from Janzen et al. (2003) in place of clover and perennial grass,
- 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 soil were found to be losing soil organic carbon to the atmosphere based on the results of the Holos modelling. 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}) (based on analysis of change in soil organic carbon resulting from Holos modelling as described in section 4.2.1.2.5.2)
- 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 modelling.

3.2.2.3.2.2 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 volatilised from managed soils" (IPCC, 2006, p. 21). The indirect N_2O volatilization equation for organically managed soils appears as 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.

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

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 of (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).

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

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 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)
- 0.9 = 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)
- $Frac_{leach\text{-}[H]}$ = 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) (from CSRC (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 A.6.4-22)

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

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

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) Table 5-1)

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 (Environment and Climate Change Canada, 2022). Based on the methodology outlined in the NIR report part 2 (2022), N is estimated based on parameters that vary by agricultural ecodistricts, which is one level within Canada's National Ecological Framework. There are 1,027 ecodistricts in Canada that are characterized by landforms, geology, soil, vegetation, water bodies and fauna (NIR Part 2, 2022) (see Appendix E for Western Canadian ecozone and ecodistricts). There is a country-specific emission factor (i.e. rates of leakage and loss) for agricultural soils that is calculated for each ecodistrict 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 within which the agriculture occurs. Uncertainties in emissions factors range from 20 to 50% based on IPCC methodology (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, emissions 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 characteristics 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, oats and rye 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.

The fifth sensitivity analysis related to nitrogen emissions factors results from a meta-analysis from 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 impact category. Results of the sensitivity analysis are discussed in detail in Section 3.3.3.2.

3.2.2.3.2.3 Phosphorous 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:

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})

3.2.2.3.2.4 Changes is 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). Despite SOC's important roles, assessing the impact of SOC on agricultural systems in life cycle assessment studies is remarkably absent, notably due to a lack of clearly defined procedures (Bessou et al., 2020; Goglio et al., 2015). Given the importance of SOC on soil processes and its potential to mitigate against climate change effects, including the assessment of SOC in this and other studies is critical.

A literature review, detailed in Chapter 2 of this thesis, explores the current approaches to modelling SOC flux in mid-latitudinal, 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. One SOC modelling approach that emerged from the literature review was the IPCC Tier 2 simple C model. Studies show, when tested, the IPCC Tier 2 model was able to closely estimate real-life SOC measurements, 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 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 flux 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 (Figure 11) (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.

Figure 11. 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)

The Holos user can then define the run-in 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 used in Holos as the default setting 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÷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.

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). Moreover, there is 44% uncertainty associated with modeling SOC changes and CO_2 emissions (Environment and Climate Change Canada, 2022). As a result of limited credibility in SOC accounting and robust modeling, there is great uncertainty associated with SOC changes. However, this is partially 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. 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 run-in 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 original modelling of SOC levels using 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 found in Section 3.3.3.3.

3.3 Results

3.3.1 Overview of Farms Modelled

A total of 16 farms located in the Prairie provinces of Alberta, Manitoba, or Saskatchewan provided inventory data for one or more of the three cereal crops of interest (Table 3). These farms provided a total of 27 farm-cereal crop combinations: 10 oats, 5 rye, and 12 wheat. The total area covered by the farm-crop combinations (i.e., land occupation per year to grow one crop, which differs from the total land area of the farms since several of these crops are grown on the same plot of land in different years) is 2,821.4 hectares, averaging 104.5 hectares per farm-crop combination. The average yield of the farms is described in Table 5. In general, the farms for which inventory data were provided for this study had higher yields than had previously been reported for organic farms in the region (Table 4).

Table 4. Comparison of average yields of organic Canadian Prairie oat, rye, and wheat farms reporting inventory data with previously described average yields in tonnes per hectare.

Crop	This Study Average Yield	Average Prairie Yield	Study Average Alberta Yield	Average Alberta Yield	Study Average Manitoba Yield	Average Manitoba Yield	Study Sask. Average Yield	Average Sask. Yield
Oat	2.92	1.81[a]	3.17	2.82[d]	-	3.21[f]	2.86	2.96[f]
Rye	3.34	2.51[b]	5.92	3.63[d,e]	3.96	1.35[g]	2.27	2.76[e,h]
Wheat	1.57	2.31[c]	3.20	1.75[d]	1.38	1.31[f]	1.22	1.35[f]

Source Notes: a) Entz et al. (2001) average of yield ranges of oat, oat/alfalfa, and oat/clover. b) Entz et a. (2021) an average of yield range of fall rye. c) Entz et al. (2001) an average of yield ranges of HRS wheat, soft white spring wheat, and durum wheat. d) Alberta Farmer Express (2021). e) Döring and Neuhoff's (2021) value of organic yields is 26% less than the conventional yield for cereal crops. f) Arnason (2015). g) Manitoba Agriculture Resource Development (2022). h) Government of Saskatchewan (2021).

The farms analyzed varied not only in size and yield, but also in management practices and total production output. Table 5 gives a breakdown of the various crop rotations seen through the 16 Prairie farms where data was collected from.

Table 5. Overview of rotation sequences seen in the 16 Prairie farms studied. The numbers in the brackets with the oats, rye, and wheat indicate total tonnage produced of that crop in one year (i.e., production output). Brackets with N.D indicated no data was available and those crops were not modelled. Where there are multiple rotation occurrences (i.e., more than one farm implemented the same rotation), multiple brackets appear to show the various production outputs of each occurrence.

Rotation 1	**Rotation 2**	**Rotation 3**	**Rotation 4**	**Rotation 5**	**Rotation 6**	**Rotation 7**	**Rotation 8**	**Rotation 9**	**Rotation 10**
Peas	Oats [386]	Alfalfa	Wheat [87]	Oats [174]	Wheat [6]	Soy	Oats [920] [409]	Rye [240] [321]	Wheat [74] [46] [57] [304]
Wheat [210]	Barley [N.D]	Oats [177] [1,498]	Oats [81]	Wheat [59]	Oats [21]	Wheat [2,177]			
	Rye [N.D.]		Rye [134]	Barley	Rye [56]				
	Wheat [N.D.]			Clover	Lentils				
				Wheat [59]	Wheat [94]				
				Oats [108]	Lentils				
				Barley	Rye [222]				
				Clover	Clover				
				Wheat [123]					
				Oats [262]					
Rotation Occurrences									
1	1	2	1	1	1	1	2	2	4

Based on the limited number of survey respondents and subsequent crop-specific LCI data collected, and to maintain participant anonymity, life cycle impact assessment results are aggregated by crop and reported as average Prairie crop-specific production impact contributions. Therefore, results are presented as weighted averaged organic oat production consisting of 10 oat farm-crop combinations, weighted averaged organic rye production system consisting of 5 rye farm-crop combinations, and weighted averaged organic wheat system consisting of 12 wheat farm-crop combinations. Due to the limited farm-crop combinations constituting these average Prairie systems, it is not recommended that the results of this analysis be extrapolated for all organic Prairie oat, rye, and wheat production systems.

3.3.2 Impact Assessment

Cradle-to-harvest gate life cycle impact assessment results are formally reported for six impact categories: climate change (long term) (CC), fossil and nuclear energy use (EU), freshwater acidification (FA), freshwater eutrophication (FE), freshwater ecotoxicity (FX), and land occupation, biodiversity (LO). However, results for an additional seven impact categories appear in Appendix U: ionizing radiation, mineral resource use, ozone layer depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, and water scarcity, in the form of both the production weighted average and arithmetic average. Results are presented as a weighted average based on production tonnage output (Table 6). The production weighted averages were calculated using Equation 6 shown below:

Equation 6*: Production Weighted Average =*

$$\frac{((Emissions\ A \times Production\ Ouput\ A)+(Emissions\ B \times Production\ Output\ B)\ldots+(Emissions\ X \times Production\ Output\ \times))}{(Production\ Output\ A+Production\ Ouput\ B\ldots+Production\ Output\ X)}$$

Where

- Emissions A = total emissions per FU for the first crop in the averaging sequence (unit varies by impact category) (LCA modelling results)
- Production Output A = total tonnage produced of the first crop in the averaging sequence (tonnes) (LCI data)
- Emissions B = total emissions per FU for the second crop in the averaging sequence (unit varies by impact category) (LCA modelling results)
- Production Output B = total tonnage produced of the second crop in the averaging sequence (tonnes) (LCI data)
- Emissions X = total emissions per FU for the last crop in the averaging sequence (unit varies by impact category) (LCA modelling results)
- Production Output X = total tonnage produced of the last crop in the averaging sequence (tonnes) (LCI data)

Though detailed impact assessment contributions are available for very specific activities (e.g., tilling, manure transport, etc.,.), for ease of reporting, some impact assessment results have been aggregated into activity groups “Nutrient Application” and “Field Operations”. For example, nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop (i.e., impacts from soy), mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Similarly, field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production. Negative SOC values represent carbon sequestration while positive SOC values indicate carbon dioxide loss to the atmosphere. “Seed Inputs” are emissions associated with seed provisioning. A complete breakdown of contributions from each individual source (i.e., uncategorized) for each impact category is available in Appendix U. Moreover, a compiled visualization of each assessed impact category and its contributions on a weighted and arithmetic average is available in Appendix V. Table 6 shows the cradle-to-harvest life cycle assessment results for 1 tonne harvested organic Western Canadian oat, rye, and wheat for the impact categories of CC, EU, FA, FE, FX, and LO.

Table 6. Cradle-to-harvest life cycle assessment results for 1 tonne harvested organic Western Canadian oat, rye, and wheat for the impact categories of CC, EU, FA, FE, FX, and LO.

	Wheat	Oats	Rye
Climate Change (long term) ($kg\ CO_2$ eq)	79.6	134	116
Fossil and Nuclear Energy Use (MJ Deprived)	2720	2370	2860
Freshwater Acidification ($kg\ SO_2$ eq)	5.10E-11	8.12E-11	1.48E-10
Freshwater Eutrophication ($kg\ PO_4^-$ lim eq)	0.0168	0.0228	0.0119
Freshwater Ecotoxicity (CTU e)	3.89E6	2.86E6	2.79E6
Land Occupation, Biodiversity (m^2 arable land eq yr)	3.35	2.31	2.31

Looking at production weighted averages, the net contributions to CC for the three crops considered ranged from 79.6 kg CO_2-e per tonne of wheat, 116 kg CO_2-e per tonne of rye, and 134 kg CO_2-e per tonne of oats produced under organic management on the Prairies (Figure 12). Importantly, there was substantial SOC sequestration in all crops. As a result, net long term climate change impacts of growing wheat, rye, and oats under organic management on the Prairies were substantially lower than they would otherwise have been if change in SOC had not been included in the analyses (Figure 12). Soil organic carbon makes up 40% of overall CC impacts to organic wheat, 33% of those associated with organic oats, and 41% of those of organic rye farmed on the Canadian Prairies. Nutrient application makes up a large share of emissions for each crop: 44% of emissions for rye, 49% of emissions for oats, and 79% for rye. Much of this comes from direct and indirect nitrous oxide emissions resulting from applied nitrogen in the form of manures, organic amendments, green manures, and crop residues. On the weighted average basis, N_2O emissions comprised 17% of wheat emissions, 25% of oat CC emissions, and 37% of rye CC emissions. Field operations play a more impactful role in wheat and oat production than in rye, with field operations constituting 44% of total wheat CC emissions, 38% of oat emissions, and only 18% of rye emissions (Figure 12). Seeds are less dominant to CC emissions, making up only 11%, 12% and 3% of wheat, oats, and rye emissions respectively (Figure 12).

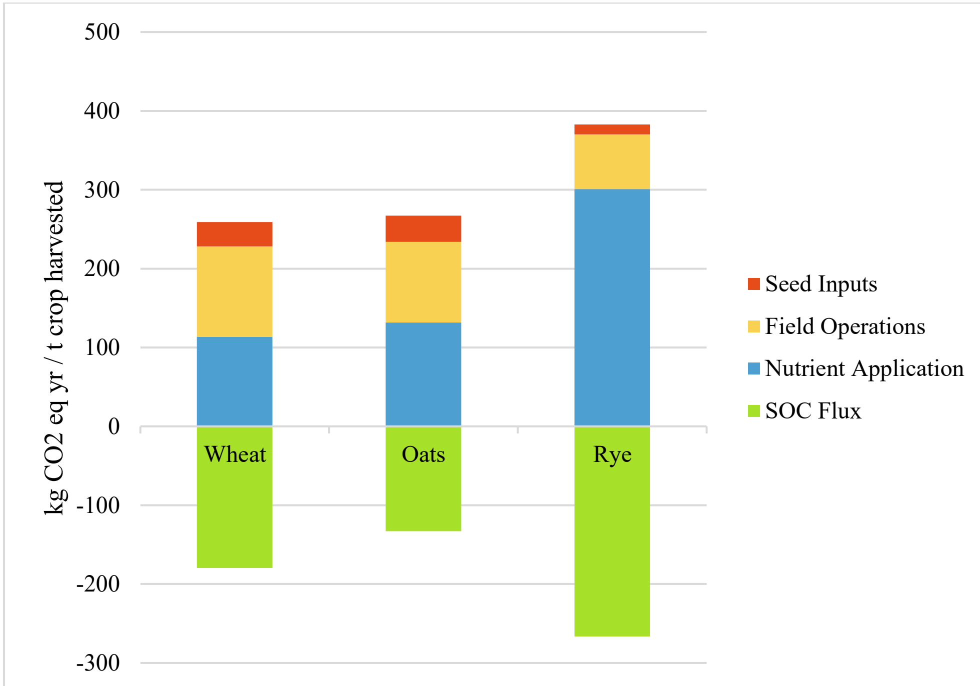

Figure 12. Cradle-to-harvest gate climate change (long term) impacts of Western Canadian organic wheat, oats, and rye on a per tonne harvested production weighted output basis. "SOC Flux" includes field level carbon dioxide emissions from crop production. "Nutrient Application" includes application of organic amendments such as manures, green manures, cover crops, mineral amendments, and field level nitrous oxide emissions. "Field Operations" encompasses the use of all farm machinery for crop production. "Seed Inputs" incudes seed provisions.

In the resource depletion impact category of Fossil and Nuclear Energy Use the weighted average EU impact contributions varied from 2,370 MJ deprived per tonne of oats, to 2,720 MJ deprived for wheat and 2,860 MJ deprived per tonne of rye produced (Table 6). Results of wheat and oats see a majority of EU impacts coming from field operations activities: 58% and 57% of total EU impacts respectively (Figure 13). In contrast, in organic rye production, the greatest source of EU impacts arose from the nutrient application inputs (62%) and only 34% of impacts arose from field operations (Figure 13).

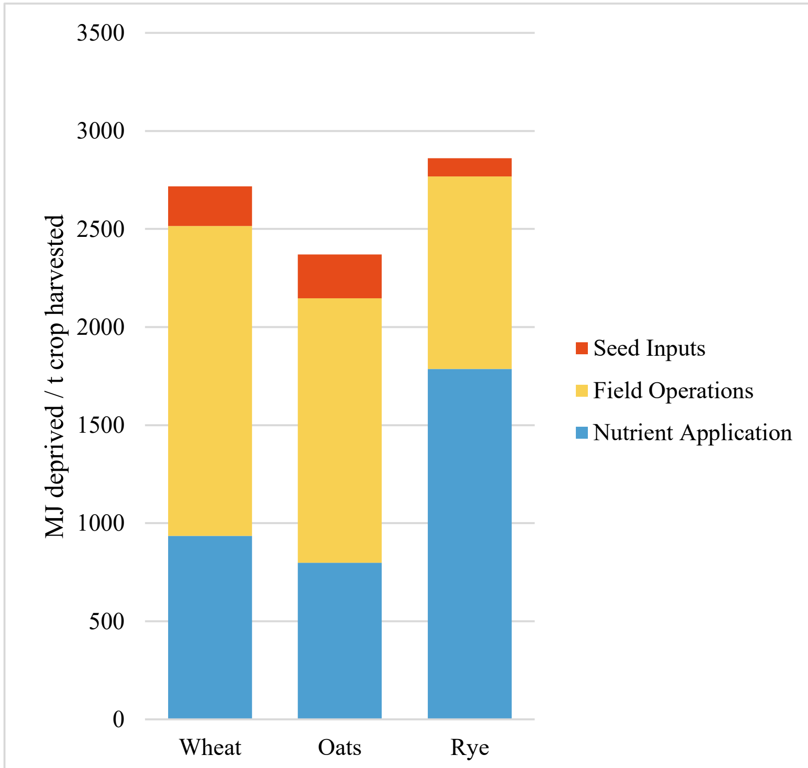

Figure 13. Cradle-to-harvest gate fossil and nuclear energy use impacts of Western Canadian organic wheat, oats, and rye on a per tonne harvested production weighted output basis. "Nutrient Application" includes application of organic amendments such as manures, green manures, cover crops, mineral amendments. "Field Operations" encompasses the use of all farm machinery for crop production. "Seed Inputs" incudes seed provisions.

Turning to freshwater acidification results, results were 5.10E-11 for wheat, 8.12E-11 for oats, and 1.48E-10 for rye on the production weighted average basis (Table

6). Hotspots in the freshwater acidification life cycle impacts of Western Canadian organic cereal crop production are nutrient application impacts from field level emissions including soil nitrate, ammonia, and nitrogen oxides emissions (Figure 14). Nitrate impacts, falling within the nutrient application category, constitute 48% of total FA impacts for wheat, 54% for oats, and 46% for rye. Ammonia impacts, also within the nutrient application category, make up 26% of total FA impacts for wheat, 31% for oats, and 39% for rye. Additionally, nitrogen oxides within the nutrient application category constitute 4% of total wheat FA impacts, 5% for oats, and 7% for rye. These large impacts from field level emissions (i.e., nitrate, ammonia, and nitrogen oxides) come from green manures and crop residues, as these were the biggest inputs.

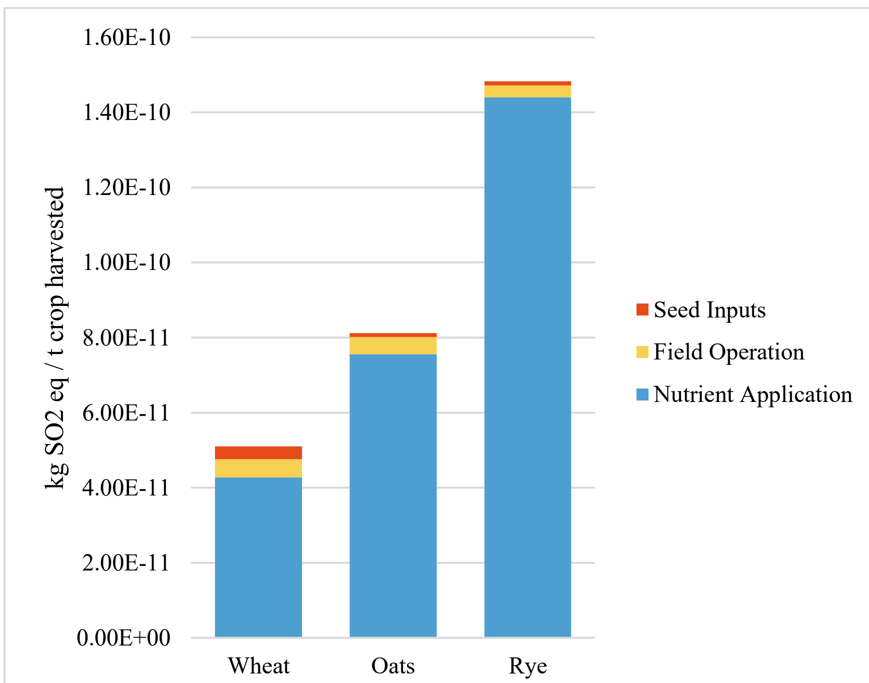

Figure 14. Cradle-to-harvest gate freshwater acidification impacts of Western Canadian organic wheat, oats, and rye on a per tonne harvested production weighted output basis. "Nutrient Application" includes application of organic amendments such as manures, green manures, cover crops, mineral amendments, and field-level emissions (ammonia, nitrate, and nitrogen oxides). "Field Operations" encompasses the use of all farm machinery for crop production. "Seed Inputs" incudes seed provisions.

When looking at contributions to freshwater eutrophication, impacts were 0.0168 for wheat, 0.0228 for oats, and 0.119 kg PO_4^- lim eq per tonne crop harvested for rye (Table 6). The dominant source of impacts for freshwater eutrophication for all crops was nutrient application. Nutrient application made up 80% of total EU impacts for wheat, 91% for oats, and 86% for rye (Figure 15). The source of these nutrient application impacts mainly came from phosphate in the form of mineral amendments and manures. Phosphate made up 71%, 83%, and 46% of total EU impacts for wheat, oats, and rye respectively. Field operations were of minimal contribution to EU: making up only 3-5% of impacts for each crop (Figure 15). Seed inputs constituted a larger share of impacts, with 14% of total wheat EU impacts coming from seed inputs, only 5% for oats, and 9% for rye (Figure 15).

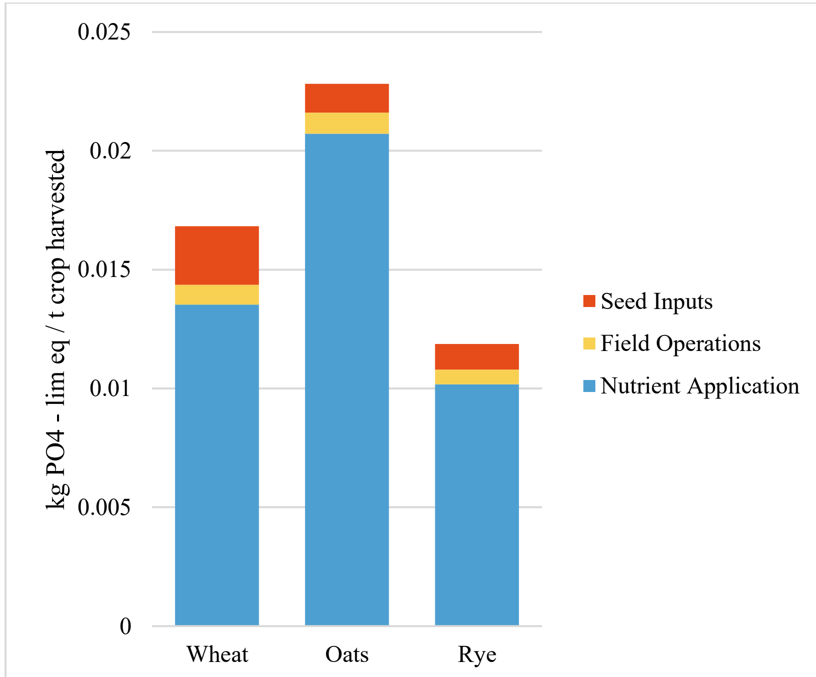

Figure 15. Cradle-to-harvest gate freshwater eutrophication impacts of Western Canadian organic wheat, oats, and rye on a per tonne harvested production weighted output basis. "Nutrient Application" includes application of organic amendments such as manures, green manures, cover crops, mineral amendments, and field-level emissions (phosphate). "Field Operations" encompasses the use of all farm machinery for crop production. "Seed Inputs" incudes seed provisions.

Impacts to freshwater ecotoxicity are 3.98E6 for wheat, 2.86E6 for oats, and 2.79E6 CTUe per tonne crop harvested for rye (Table 6). Field operations are the most impactful to the FX category for the wheat and oats crop, making up 61% and 63% of total FX impacts respectively, while field operations make up only 43% of total rye FX impacts (Figure 16). Nutrient application makes up 30% of total wheat impacts, 24% for oats, and 52% for rye. The nutrient application impacts come from a range of sources including green manures and manure. In wheat, green manure impacts make up 5% of FX impacts, in oats GMs make up 21% of impacts, and in rye they make up 51% of FX impacts (Figure16). Seed inputs are less influential to the FX category, but still important as they constitute 8% of total wheat FX impacts, 13% for oats, and 5% for rye (Figure 16).

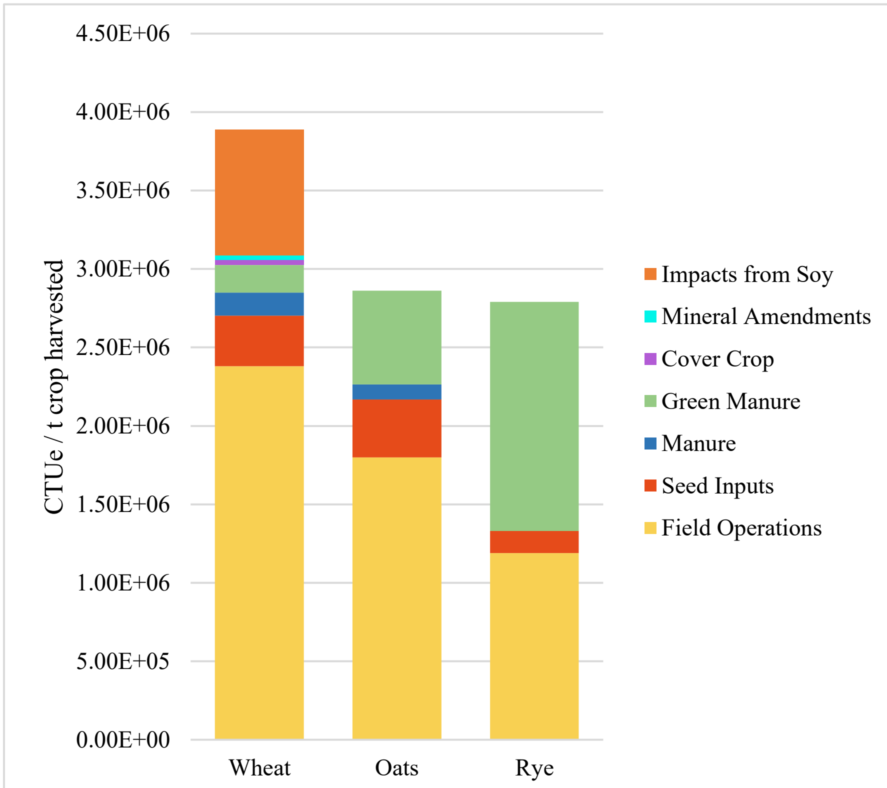

Figure 16. Cradle-to-harvest gate freshwater ecotoxicity impacts of 1 tonne Western Canadian organic wheat, oat, and rye crop. "Impacts from Soy" includes the inherited environmental impacts from the soy crop grown immediately prior in the crop rotation which contributed nitrogen to help the subsequent crop grow. "Field Operations" encompasses combine harvested, sowing, fertilizing, harrowing (spring tine and rotary), rolling, disking, ploughing, chiseling, hoeing, and weeding.

The last impact category considered, and second related to a critical resource dependency, is land occupation, biodiversity impacts. Impacts from LO on the production weighed average are 3.35 for wheat, 2.31 for oats, and 2.31 m^2 arable land eq yr per tonne crop harvested for rye (Table 6). For wheat, the field operations make up the majority of impacts (54%) followed by nutrient application (40%) and seed inputs (6%) (Figure 13). Oats are similar to wheat, with most of the impacts coming from field operations (58%), then from nutrient application (33%), and lastly from seed inputs (10%) (Figure 17). Rye, however, is dominated by impacts from nutrient application (62%). Like the FX category, these nutrient application impacts are coming from sources of manures and green manures. Wheat green manure impacts make up 5% of total LO impacts, oats GM impacts make up 28% of LO impacts, and rye GMs constitute 62% of total LO impacts (Figure 17). Field operations make up 34% of total LO impacts to rye, followed by 4% from seed inputs (Figure 17).

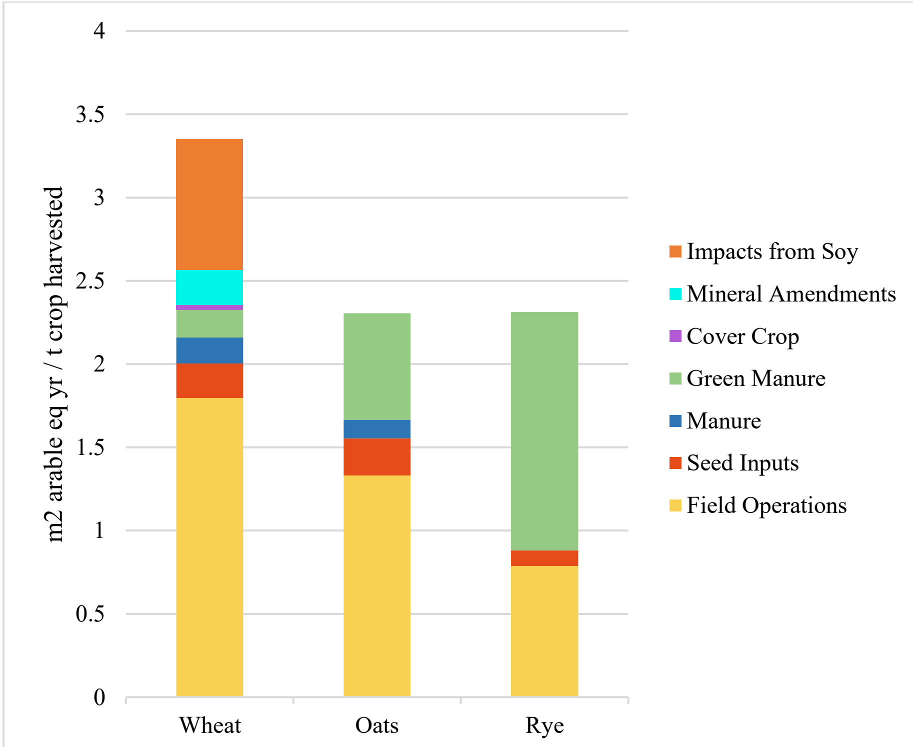

Figure 17. Cradle-to-harvest gate land occupation, biodiversity impacts of 1 tonne Western Canadian organic wheat, oat, and rye crop. "Impacts from Soy" includes the inherited environmental impacts from the soy crop grown immediately prior in the crop rotation which contributed nitrogen to help the subsequent crop grow. "Field Operations" encompasses combine harvested, sowing, fertilizing, harrowing (spring tine and rotary), rolling, disking, ploughing, chiseling, hoeing, and weeding.

3.3.3 Sensitivity Analysis

A sensitivity analysis is a tool used in LCA to assess the validity of results and how sensitive they may be to uncertainty factors (Wei et al., 2015). A total of nine sensitivity analyses were undertaken to assess the effect of changes in assumptions and input parameters used on overall results: two related to how impacts of green manures were modeled; five related to the emissions factors applied to estimate direct and indirect N_2O emissions from soils, and two were associated with how the Holos model used to estimate annual losses or gains in soil organic carbon was initiated.

3.3.3.1 Green Manures

The first sensitivity analysis of green manure tested the uncertainty around the green manure allocation. In the baseline scenario, used in the above analysis, GM impacts were allocated 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 8). In the sensitivity analysis, 100% of GM or leguminous crop impacts were placed solely on the succeeding crop. Results of the sensitivity analysis conducted appear in Table 7 and report results of allocating all impacts associated with growing a green manure on the immediately succeeding crop in a rotation rather than across all subsequent crops in proportion to the nitrogen contents of their harvested fraction.

Table 7. Results of the green manure sensitivity analysis testing the uncertainty of the GM allocation method. Results of all impact categories are presented on the production weighted output basis alongside the baseline modelling results in addition to the calculated percent changes between the baseline and sensitivity results.

	CC (kg CO_2 eq)	**EU** (MJ Deprived)	**FA** (kg SO_2 eq)	**FE** (kg PO_4^- lim eq)	**FX** (CTU e)	**LO** (m^2 arable land eq yr)
Wheat (baseline)	79.6	2720	5.10E-11	0.0168	3.89E6	3.35
Wheat (sensitivity)	72.8	2620	5.05E-11	0.0167	3.82E6	3.28
%Δ Wheat	-8.54%	-3.68%	-0.980%	-0.595%	-1.80%	-2.90%
Oats (baseline)	134	2370	8.12E-11	0.0228	2.86E6	2.31
Oats (sensitivity)	92.5	1770	7.87E-11	0.0221	2.44E6	1.82
%Δ Oats	-30.9%	-25.3%	-3.08%	-3.07	-14.7%	-21.2%
Rye (baseline)	116	2860	1.48E-10	0.0119	2.79E6	2.31
Rye (sensitivity)	122	2890	1.51E-10	0.0119	2.82E6	2.33
%Δ Rye	-5.17%	-1.05%	-2.03%	0.00%	1.08%	0.865%

Although shifting the GM allocation methodology impacted the inventories of only eight individual farms, this affected the overall impacts of the average wheat, oat, and rye systems. Most individual farm-crop emissions decreased since their GM impacts dropped to zero. This is because many modelled crops were nested within a rotation and did not fall directly after the cultivation of a GM. All crops whose GM impacts dropped to zero were either wheat or oats. Only one individual farm-crop combination, a rye crop, had its GM impacts increase. Instead of receiving a fraction of GM inputs, it received 100% of GM inputs. The differences in these allocation methodologies can be seen by comparing results reported in Table 7. On a production weighted average basis, overall changes to wheat and rye were relatively small compared to those of oats. For example, the CC impacts decreased 6.8 kg CO_2 eq per tonne of wheat and increased 5.86 kg CO_2 eq for rye, but increased 41.8 kg CO_2 eq per tonne of oats harvested. Similar patterns are found across all impact categories. It should be noted that oats are particularly sensitive to this methodological choice since so many oat crops were embedded in rotations that included one or more GMs. However, all crops were affected by this sensitivity analysis and therefore, the model should be considered sensitive to this assumption.

An additional sensitivity analysis was performed on all green manures. Green manure processes were again modified to best represent Western Canadian production conditions, but this time a standard yield of 2,000 kg ha^{-1} was assumed for all GMs (Thiagarajan et al., 2018), rather than using the original LCI data to inform a yield. The 2,000 kg ha^{-1} yield is higher than the LCI yield data for lentils, peas, and clover, but lower than the LCI yield data for alfalfa. Results of this sensitivity analysis are found in Table 8.

Table 8. Results of the green manure sensitivity analysis testing the uncertainty of the GM LCI data. Results of all impact categories are presented alongside the baseline modelling results in addition to the calculated percent changes between the baseline and sensitivity results.

	CC (kg CO_2 eq)	**EU** (MJ Deprived)	**FA** (kg SO_2 eq)	**FE** (kg PO_4^- lim eq)	**FX** (CTU e)	**LO** (m^2 arable land eq yr)
Wheat (baseline)	79.6	2720	5.10E-11	0.0168	3.89E6	3.35
Wheat (sensitivity)	67.8	2550	5.04E-11	0.0166	3.76E6	3.23

%Δ Wheat	-14.8%	-6.25%	-1.18%	-1.19%	-5.53%	3.58%
Oats (baseline)	134	2370	8.12E-11	0.0228	2.86E6	2.31
Oats (sensitivity)	123	2180	1.19E-10	0.0234	2.66E6	2.04
%Δ Oats	-8.21%	-8.02%	46.6%	2.63%	-6.99%	-11.7%
Rye (baseline)	116	2860	1.48E-10	0.0119	2.79E6	2.31
Rye (sensitivity)	54.4	2130	1.45E-10	0.00999	2.20E6	1.71
%Δ Rye	-53.1%	-25.5%	-2.03%	-16.1%	-21.1%	-26.0%

In the original modelling outcome, green manures made up 4% of total climate change impacts for wheat on a production weighted average. They made up 15% of total CC impacts for oats and 24% for rye on a production weighted average. After increasing yields of GM across the board to 2,000 kg ha^{-1}, GM impacts made up only 1% of total CC impacts for wheat, 12% for oats, and 16% for rye. Wheat decreased by 14.8% in CC impacts with this shift in green manure input data (Table 8). The CC impacts of oats decreased by 8.21% per tonne and those of rye decreased by 53.1% per tonne harvested on a production weighted average basis (Table 8). Notably, the oats weighted average saw an increase in freshwater acidification (46.6%) and freshwater eutrophication (2.63%) (Table 8). This is because one individual farm amongst the 10 modeled was receiving 100% of GM impacts. This sensitivity analysis effected each crop differently, as did the different impact categories. Nonetheless, the effects of this sensitivity analysis were sufficiently notable that the model should be considered sensitive to this uncertainty.

3.3.3.2 Effect of Changing Emissions Factors Used in Estimating N_2O losses to the Atmosphere

To test the effect that changes to emissions factors have on estimates of CC results from growing wheat, oats and rye under organic management, a series of sensitivity analyses were performed (Table 9). 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): The fifth sensitivity analysis related to nitrogen emissions factors results from a meta-analysis from Charles et al. (2017). To test the effect of this fifth alternative, EF_1F_{on} was replaced with the suggested 0.57% value in Equation 1.

Table 9. Results of the EF sensitivity analysis testing the uncertainty of the various emissions factors. Results of the climate change (long term) impact category are presented alongside the baseline modelling results in addition to the calculated percent changes between the baseline and sensitivity analysis results

	kg CO_2 / t crop harvested	**+/-20% and +/-50% change in EFs (kg CO_2 eq / t crop harvested)**					**Difference between baseline and EF change (%)**				
	Baseline	-20%	+20%	-50%	+50%	Charles et al. (2017)	Δ-20%	Δ+20%	Δ-50%	Δ+50%	Charles et al., (2017)
Wheat	79.6	71.1	104	64.7	112	84.5	-10.7%	30.7%	-18.7%	40.7%	6.16%
Oats	134	120	148	99.9	169	138	-10.4%	10.4%	-25.4%	26.1%	2.98%
Rye	116	88.3	145	45.0	184	111	-23.9%	25.0%	-61.2%	58.6%	-4.31%

Results of the five sensitivity analyses undertaken related to changes in the emissions factors applied to estimate direct and indirect N_2O emissions from soils performed as expected in that decreases in EFs resulted in an overall decrease in CC impacts associated with soil emissions, while increases in EFs resulted in an overall increase in CC impacts (Table 9). For wheat on a production weighted average basis, a 50% decrease in EFs resulted in a decrease of 18.7% while a 20% decrease in EFs resulted in a decrease of 10.7% per tonne of wheat produced relative to the base case modeling (Table 9). Increasing the EFs by 20% resulted in production weighted average CC impact contributions for wheat increasing by 30.7% per tonne harvested, while a 50% increase in the EF values applied resulted in a 40.7% per tonne harvested emission increase relative to the base case analysis (Table 9). Applying the 0.57% emission factor that results from the meta-analysis undertaken by Charles et al. (2017) had a more nuanced effect. This is because it was higher than some reconciliation unit specific EFs applied in the base case analysis but lower than others (e.g. in RU 34 the EF was 0.79% while in RU 30 the EF was 0.43%). As a result, the production weighted average emissions associated with wheat production increased by only 6.16% per tonne using the Charles et al. (2017) EF value (Table 9).

Turning to how changes in EF affected modeled CC emissions from oat production, in general the patterns were very similar to those described above for wheat (Table 9). When EFs were decreased by 50%, the production weighted average CC emissions of oat decreased by 25.4% while a 20% reduction in the EFs applied, resulted in a CC emission decrease 10.4% relative to the base case analysis (Table 9). A 20% increase in EFs resulted in a 10.4% increase in GHG emissions of oat production on a weighted average basis while a 50% increase in EFs resulted in a 26.1% increase in emissions (Table 9). Also similar to wheat, using the constant EF from Charles et al. (2017) resulted in a small increase of CC emissions of 2.98% associated with oat production on a weighted average basis due to the value being higher than some of the original EFs used (Table 9).

Production weighted average CC emissions associated with rye production again mirrored the pattern seen in wheat and oats. A 50% across the board reduction in EFs applied resulted in a decrease of 61.2% per tonne of rye produced while a decrease of 20% in the EFs applied resulted in a 23.9% per tonne emission reduction relative to the base case modeling (Table 9). Increasing the EFs by 20% resulted in GHG emission increase of 25.0% per tonne of rye harvested, while increasing the EFs by 50% resulted in an emission increase of 58.6% per tonne of rye produced over the base case analysis. Unlike wheat and oats, however, when applying the EF value from Charles et al. (2017) the production weighted average emission for rye decreased by 4.31% per tonne harvested.

Emissions, on a production weighted average shifted proportionally for wheat and oats relative to the scale of the change in the EF applied. Rye appears to have shifted most dramatically with the changes to EFs. This is likely due to the low sample size (n=5) of rye farm-crop combinations compared to wheat (n=12) and oats (n=10). Moreover, rye reacted opposite to that of wheat and oats when using the Charles et al. (2017) EF. This is likely because several individual farms growing rye were located in RUs for which prescribed EFs from the National Inventory Report (2022) were higher than the Charles et al. (2017) value. Therefore, a switch to the lower Charles et al. (2017) value dropped the overall CC emissions associated with organic rye production in contrast to the pattern observed in oats and wheat. Overall, the low sample size of rye makes it the most sensitive to emission factor uncertainty. However, all crops experienced a substantial change in overall emissions, particularly when increasing and decreasing EFs by 50%. Therefore, the modelling should be considered sensitive to emissions factors.

3.3.3.3 Model Run in Period Impact on Soil Organic Carbon

As outlined previously in detail, there is 44% uncertainty associated with modelling changes in soil organic carbon (National Inventory Report, 2020). Therefore, a sensitivity analysis was performed on the Holos model run-in periods. Results of the sensitivity analysis on climate change (long term) are found in Table 10.

Table 10. Results of the SOC sensitivity analysis testing the uncertainty of the Holos run-in times. Results of the climate change (long term) impact category are presented alongside the baseline modelling results in addition to the calculated percent change between the baseline and sensitivity analysis results.

	Run-in Time (kg CO_2 eq / t crop harvested)			**Difference between baseline results and change in run-in time (%)**	
	Baseline (15-year run-in)	5-year run-in	20-year run-in	%Δ 5-year run-in	%Δ 20-year run-in
Wheat	79.6	48.0	86.1	-39.7%	8.17%
Oats	134	88.5	196	-34.0%	46.3%
Rye	116	98.5	122	-15.1%	5.17%

For the 5-year run-in period, year-on-year rates of soil organic carbon sequestration values under current management are higher than they were in the base case analysis when a 15 year run-in period was used, and subsequently net climate change impacts are lower, for all three crops grown (Table 10). On a weighted average basis, net CC impacts decreased by 39.7% per tonne of wheat produced, 34.0% per tonne of oats, and 15.1% per tonne of rye harvested (Table 10). While each crop was affected differently by the 5-year run-in period, this comes down to an individual farm basis. Moreover, although oats experienced the greatest shift in impacts, all farms and crops were sensitive to the 5-year run-in period.

For the 20-year run-in period, annual rates of soil organic carbon sequestration were lower than they had been under the base case run-in period of 15 years and as a result the net CC impacts increased for all crops (Table 10). On a weighted average basis, wheat CC impacts increased by 8.17%, oat by 46.3%, and rye by 5.17%. The major shift in oats is due to one individual farm that shifted from a SOC sequestering farm to an emitting farm. This then had a knock-on effect on soil-related N_2O emissions that resulted from the loss of soil organic matter. Neither wheat or rye had any farms shift from sequestering to emitting, which made them less sensitive to the 20-year run-in period shift than oats. However, all farms were impacted by shift and should be considered sensitive to the run-in period.

3.4 Discussion

The aim of this research was to assess the net life cycle environmental impacts of Canadian Prairie oat, rye, and wheat cropping systems, specifically climate change (long term), fossil and nuclear energy use, freshwater acidification, freshwater ecotoxicity, freshwater eutrophication, and land occupation; and to understand the contribution of soil organic carbon to climate change (long term) impacts. The following discussion will outline drivers of those environmental impacts and how the impacts compare to the literature.

The net climate change (long term) impacts from all crops are net positive. This means that organic management practices are not sequestering enough carbon to offset total life cycle GHG emissions associated with the production of an average tonne of organically farmed wheat, rye or oats on the Prairies. These values are broadly consistent with some findings from LCA of agricultural systems where changes in soil organic carbon were also assessed. However, much depends on local conditions. For example, one of the experimental field sites Goglio et al. (2014) analyzed that was under long-term conventional management practices in Alberta, was found to be sequestering SOC at a rate equal to 30% of GHG emissions from all other sources, an offsetting rate broadly similar to what this research found. In contrast, however, at another site in Alberta under identical management but on different soils, SOC was being released to the atmosphere at a rate that those SOC flux related emissions contributed 23% of total CC impacts at that site (Goglio et al 2014). More closely aligned to the results of this analysis, Prechsl et al. (2017), reporting on organic Swiss field crops, reported that soil carbon emissions made up 39.6% of total life cycle CC contributions. The results of this analysis show that the farms growing organic wheat, oats and rye are, on balance, sequestering carbon in their soils consistent with what is typical of Western Canadian farms (Figure 18) (Agri-food Canada, 2016).

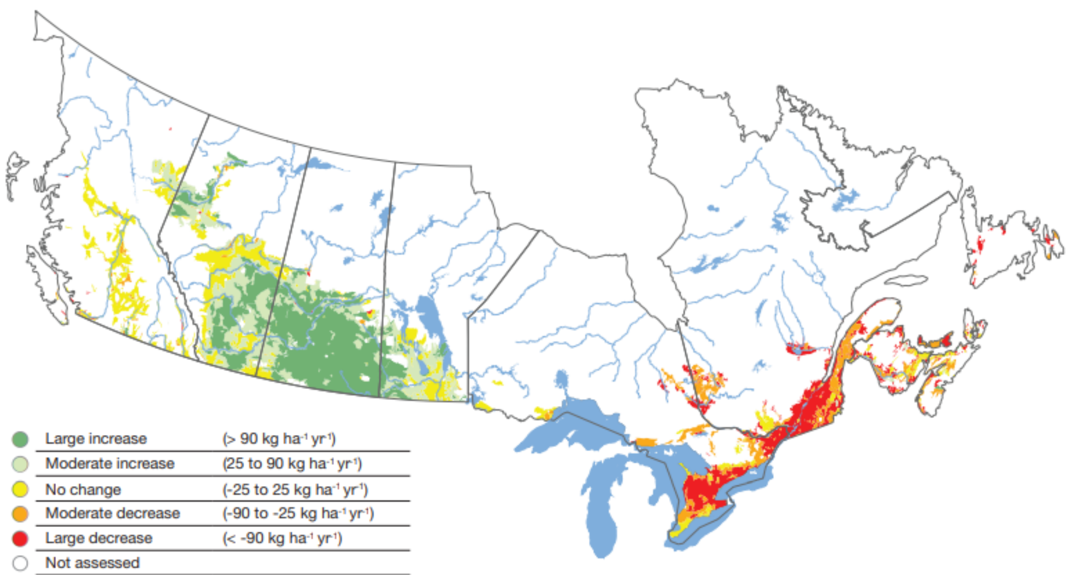

Figure 18. Soil organic carbon change (kg C ha-1 yr-1) in Canada in 2011 (Agriculture and Agri-food Canada (2016)

Importantly, variations in SOC changes occur not only through agro-climatic conditions, but also through management practices. Table 11 demonstrates the various nutrient applications that were applied to each farm-crop combination that could help explain variations in SOC changes between crops, and subsequently CC emissions.

Table 11. Overview of nutrient application treatments for each crop.

	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop
Wheat	2 Applications	6 Applications	1 Application	2 Applications	1 Application
Oats	1 Application	7 Application	-	-	-
Rye	-	4 Applications	-	1 Application	-

As displayed in Table 11, each crop had varying nutrient application treatments and management practices that could contribute to soil organic carbon changes. Additionally, the duration and complexity of crop rotations implemented on farms that provided data (Table 5), such as monocropping systems vs. rotations with as many as eight crops grown in series, can help explain the SOC differences between crops. For example, only two individual farms were found to be emitting carbon from the soil based on the modeling. Those two farms were both oat monocropping systems. Hence, average SOC sequestration for oats was lower than for wheat or rye, and subsequent CC emissions were higher for oats than for wheat or rye.

Nitrous oxide, as discussed, constitutes an important source of CC emissions: 17% of wheat, 26% of oats, and 37% of rye. However, they make a smaller contribution than has been found at other sites where SOC was also assessed. For example, Prechsl et al. (2017) found that N_2O emissions comprised 58.5% of CC emissions in organic Swiss field crops. Similarly, Goglio et al. (2014) reported N_2O emissions contributed 81% and 53% of total GHG emissions arising from the two Western Canadian field crop experimental sites under conventional management. The much lower climate impact contribution of N_2O emissions found in this research are potentially distinguishable from these earlier studies. While Prechsl et al. (2017) reported results for organic field crop production, differences in geography and the input of manure to the systems that they modeled could explain the differences. Meanwhile Goglio et al. (2014), modeled conventional Western Canadian management practices which included 75 kg of synthetic

N fertilizer per ha annually. This addition of synthetic fertilizer helps explain the discrepancies in N_2O contributions to CC impacts between the various Western Canadian systems.

In addition to nitrous oxide, hotspots to CC emissions include green manures. GM emissions make up only 7% of total CC emissions for wheat, but make up 22% of CC emissions for oats and 41% of CC emissions for rye. This is consistent with the sources of nutrients for those crops (Table 11). Amongst the farms growing oats for which we had data, the only additional nutrient inputs were derived from green manures and one instance of a manure application. Similarly, the farms for which we had data related to rye production sourced nutrients solely from green manures and one instance of mineral amendment application (Table 11). Amongst the farms for which we had data related to wheat cultivation, however, nutrients inputs were derived from a variety of sources (Table 11). Importantly, 16% of modeled wheat emissions come from a previously grown and harvested leguminous crops (i.e., impacts from soy). This comes from the assumption (detailed in Section 3.2.1.4) that soy contributes nitrogen, and related impacts, to the next crop grown in rotation, and in this case a wheat crop (Table 5). Therefore, the wheat crop inherits some of the environmental burdens of growing the soy crop, since the soy is its source of nutrients.

Accuracy of the climate change (long term) impacts may have been limited by the ability to compare crop rotations with monocropping fields. Studies often recommend that a systems thinking approach to calculating the impacts of organic agriculture is best (Jeswani et al., 2018). This is particularly true since organic agriculture must rely on alternative nutrient application methods and sources such as crop residues, rotations, and green manures. Without considering these spatial-temporal aspects of organic farming, one may be misrepresenting inputs and how they contribute to emissions or emissions reductions. Relatedly, it then becomes difficult to compare inventory datasets and resulting life cycle impacts of farm-crop combinations that arise from complex crop rotations versus monocropping systems. For example, when calculating the soil organic carbon sequestration values through Holos, we ended up with a whole farm SOC flux value that was representative of all crops grown on the farm across multiple rotations. If the system was a monocrop, the whole-farm SOC value is consistent for every crop grown. However, if the system has a rotation of two crops, the whole-farm SOC value was taken and applied to individual crops. That means that the SOC flux associated with wheat grown in an extensive rotation, for example, may partially reflect change in SOC from the other crop grown earlier in the rotation: such as soy. Comparing crop rotations with fields more accurately requires more time and careful consideration of the whole farm interactions.

Impacts for fossil and nuclear energy use for wheat and oats show that most impacts arise from field operation related activities. This finding is consistent with the literature. Notably, an organic wheat LCA from Verdi et al. (2022) found that energy use impacts were driven by machinery practices. Similarly, Pelletier and colleagues (2008) also found that fuel inputs were the main source of energy demand impacts (however, Pelletier et al., (2008) measured cumulative energy demand and not energy use, consequently results are not directly comparable). Moreover, all production weighted average values for energy use are broadly consistent with the findings of Tuomisto et al. (2012) who found that life cycle energy use associated with organic wheat production in the UK was 1,705 MJ per tonne. An additional study by Verdi et al. (2022) found that energy use of Italian organic wheat was 5,340 MJ per tonne. The energy use values from Verdi et al. (2022) are higher than those in this analysis, but could be explained by the geographic and management differences in systems.

Freshwater acidification hotspots were related to soil nitrate, ammonia, and nitrogen oxides emissions from green manures and crop residues, as these were the biggest inputs. These findings are echoed in the literature with Heurta et al., (2012), Rebolledo-Leiva et al., (2022), and Viana et al., (2022) all reporting freshwater acidification hotspots of organic systems coming from nitrate, ammonia and nitrogen oxides.

Results for freshwater eutrophication were 0.017, 0.023 and 0.012 kg PO_4-eq per t for wheat, oats, and rye respectively on a production weighted average output basis. Life cycle contributions to freshwater eutrophication arising from field crop production reported in the literature vary widely depending on the management practices, geography, and choice of the functional unit. For example, Viana et al., (2022) report a FE of 0.6 kg PO_4 eq per t for Eastern Canadian organic oats. In contrast, Williams et al., (2010) reported values of 3.6 kg PO_4 eq per t for organic European wheat. Discrepancies in the results can potentially be explained by differences in geography. In Eastern Canada, as previously discussed, the availability of manure means its use on organic farms is more prevalent. Hotspot sources of phosphate mainly come from manure and other mineral amendment applications. Therefore, the sparse use of manure on the Western Canada farms modeled here would explain the lower phosphate emissions and subsequently the lower overall FE impacts.

Freshwater ecotoxicity impacts can be difficult to compare across the literature due to the multiple units used to express FX: varying by impact assessment method. In IMPACTWorld+, the unit of measurement is CTUe, whereas in several other impact assessment methods the unit of measurement is 1.4-DCB eq. These units are not readily comparable to one another. Therefore, FX impacts expressed in units of CTUe can only be compared against impact assessment methods that use the same unit. In this analysis, it was found that wheat, oats, and rye had an FX impact of 3.89E+06, 2.86E+06, and 2.79E+06 respectively on a production weighted average basis. The majority of impacts from field operations in wheat and oats are consistent with higher general reliance on machinery inputs to organic agriculture. Much like the FE category, the use of more machinery and equipment in organic operations often arises to compensate for a lack of synthetic chemical inputs. Once again, the elevated nutrient application values in the weighted rye average may be a result of a smaller sample size compared to wheat and oats. Comparable results expressed as CTUe in a similar functional unit are limited. Fantin et al. (2017) reported an FX value of 3.2E+02 CTUe per t for conventionally grown Italian wheat. Additionally, Sørensen et al. (2021) found an FX value of 4.44E+04 CTUe per t of conventionally grown Danish wheat. Both of these values found in the literature are orders of magnitude smaller than those found in this analysis. The basis for this difference is unclear other than the difference in the conventional vs organic management systems used. The difficulty of comparing the FX units in this analysis highlights the limitation of using the IMPACTWorld+ impact assessment method. Because IMPACTWorld+ is a newer (2019) impact assessment method, few studies have used it and made available comparable LCA values.

The land occupation, biodiversity category measures the effect of land occupation on biodiversity loss over a given period of time (Bamber et al., 2020). Results of this category consider indirect land occupation including upstream land for seed provisions, upstream land related to infrastructure for fuel, etc. On a production weighted average basis, wheat is the most impactful with 3.35 m^2 arable land eq yr, followed by both rye and oats at 2.31 m^2 arable land eq yr. In both wheat and rye, much of the environmental impacts associated with nutrient application can be attributed to green manures. Six of 12 wheat crops modeled have green manure inputs and resulting impacts and 4 of the 5 rye crops have green manure impacts. Much of these embedded impacts within green manure stem from upstream/indirect land use, such as infrastructure related to fuel. Similar to FX, the LO category can only be compared to units that are the same: m^2 arable land eq yr. Once again, this showcases the limitation of using the IMPACTWorld+ impact assessment method. The creators of the impact assessment method IMPACTWorld+, used in this analysis, claim that LO "is considered an acceptable proxy for all the land use impacts on ecosystem services" (Bulle et al., 2019, p. 10). Despite this, LO impacts are seemingly very low compared to similar geographies and agricultural management practices. For example, Viana et al., (2022), who assessed organic Canadian wheat production, found that land use impacts were 1,740 m^2 per tonne crop harvested. Another example is from Van Stappen et al. (2015) who assessed Belgian organic wheat production and found that land use impacts were 1,600 m^2 per tonne crop harvested. The major discrepancy in LO impacts between values in this analysis and those reported in the literature could be attributed to the biodiversity component of this impact category. However, little additional detail is provided by the creators of IMPACTWorld+ on this impact category.

Results of all impact categories could have been affected by the limited number of datasets. This analysis is part of a larger study meant to characterize the life cycle impacts of Canadian organic field cropping system more broadly. However, the number of farmers who participated in the survey was limited. This resulted in a much smaller set of LCI data than originally anticipated. Therefore, conclusions drawn from this paper are not meant to be extrapolated to the broader Western Canadian organic field crop sector. Instead, results are merely meant to represent a small subset of Western Canadian organic farmers. That said, characterising the life cycle resource and environmental performance of organic farms using data provided by farmers working under real world conditions remains relatively uncommon. As the informal review of recent organic field crop LCA studies indicated, only seven of 16 studies elicited primary data from farmers, and none secured data from more than five farms. In this research we managed to secure data from 16 farms. The limited dataset was also associated with a set of uncertainties. As addressed in the sensitivity analysis, using the life cycle inventory data to inform green manures may have misrepresented some green manure growth in Western Canadian geographies.

Limitations should be addressed in future research. Most importantly, there is the challenge and opportunity to gather more primary data from farmers. Some of the challenges confronted in this research (e.g., travel and meeting restrictions imposed by the COVID-19 pandemic) may not be shared by past or future researchers, however, the more general underlying challenge of engaging farmer interest sufficiently to have them work through the detailed surveys required to conduct rigorous LCAs remains. Finding more effective ways to engage more farmers earlier in data collection would allow for more representative future research on Canadian organic field crop farms, and for broader conclusions to be drawn that could be extrapolated to other areas of Canada or countries with similar management practices.

The results of this analysis revealed that soil organic carbon sequestration does not offset all climate change impacts when results are presented on a production weighted output basis. However, given the locations and farm practices as modeled on the organic farms that provided data, the mostly positive increases in SOC on those farms meant that a considerable portion of other life cycle GHG emissions were offset. Future research should strive to more regularly incorporate changes in SOC in life cycle emissions of organic (and conventional) field crops for consistency or inconsistency with these results. Moreover, future research could determine how these findings could implicate climate change mitigation solutions and planning.

Certain farm management practices are associated with greater soil organic carbon sequestration. Given a larger sample of farms, future research could explore which farm management practices lead to lower total farm GHG emissions, and vice versa. Therefore, recommendations could be made about management practices that lead to a reduction in on-farm emissions. Similarly, there may be farmer demographics or characteristics that are also associated with lower total farm emissions. Future research should examine connections between farmer demographics and total farm emissions.

3.5 Conclusion

Western Canadian organic field crop oat, rye, and wheat systems were analyzed using the life cycle assessment methodology coupled with modeling of changes in farm soil organic carbon to determine their net greenhouse gas emissions and other associated environmental impacts. In total 16 active organic field crop farmers provided sufficient data to characterize inventories for 27 farm- cereal crop combinations. From these LCA results for all individual farm-cereal crop combinations were generated and aggregated to create an “average Prairie” organic wheat, oat, and rye production system. Results were presented on a production weighted average basis. The impact categories assessed were climate change (long term), fossil and nuclear energy use, freshwater acidification, freshwater ecotoxicity, freshwater eutrophication, and land occupation. Results indicate that net climate change impacts, on a production weighted average basis, were 79.6 kg CO_2 eq for wheat, 134 kg CO_2 eq for oats, and 116 kg CO_2 eq for rye. Importantly, the results of this analysis revealed that soil organic carbon sequestration does not offset all climate change impacts when results are presented on a production weighted output basis. However, given the locations and farm practices as modeled on the organic farms that provided data, the mostly positive increases in SOC on those farms meant that a considerable portion of other life cycle GHG emissions were offset. The main contributors to impact categories include changes in soil organic carbon, soil nitrogen emissions (from green manures and crop residues), and green manures. Sensitivity analyses revealed that impacts were sensitive to all of the following: how green manure impacts were allocated to subsequent crops in a rotation, green manure LCI data, the duration of the Holos run-in period used to establish a baseline soil organic carbon level, and the emissions factors applied to estimate field level nitrogen emissions. The main limitation to this analysis was the lack of more farm level LCI data. Future research should investigate organic field crops and the role of soil organic carbon to identify consistencies or inconsistencies with this analysis.

CHAPTER 4. CONCLUSION

Canada relies on its agricultural industry for food and economic prosperity (Agriculture and Agri-food Canada, 2021a). However, as climate change and rising temperatures have become an increasing concern in Canada (Environment and Climate Change Canada, 2016), the agricultural industry is also being relied on as a climate change mitigation solution. For example, the Organization for Economic Co-operation and Development (OECD) reports that agriculture could help close the gap between existing mitigation efforts and what is needed to keep global temperatures below 2°C (OECD, 2019). Furthermore, the Consultative Group for International Agricultural Research claims that agriculture can contribute significantly to climate change mitigation (Wollenberg, 2011).

Sustainable farming practices that sequester carbon [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) are described as "natural climate solutions" that will mitigate against climate change (Deacon, 2022; Drever et al., 2021). These sustainable farming practices are often associated with alternative agriculture management styles, such as organic farming. Unfortunately, methods of assessing soil organic carbon are often left out of agricultural life cycle assessments due to a lack of clear procedure for including SOC flux (Bessou et al., 2020; Goglio et al., 2015). Hence, understanding whether organic agriculture can be relied on as a climate change mitigation solution necessitates including SOC flux in LCA and analyzing the net environmental impacts of organic agricultural systems.

To determine how SOC could be included in LCA, Chapter 2 explored current approaches, modelling land management practices, and modelling SOC with organic agriculture. The literature review revealed 22 various approaches to including soil organic carbon flux with life cycle assessments. The literature review also helped to narrow down an SOC modelling approach for assessing the net environmental impacts of organic Canadian agricultural systems. Based on the land management practices it simulates and the Canadian-specific geography, Holos was chosen as the optimal SOC modelling option to integrate in this analysis.

Using the life cycle assessment methodology, Chapter 3 assesses the net greenhouse gas emissions and other associated environmental impacts of organic Canadian wheat, oat, and rye systems based in Western Canada. Importantly, as part of the GHG emissions modeling Holos was used to model soil organic carbon flux. In total, 27 farm-cereal crop combinations derived from 15 farmer surveys were used to characterize the "average" wheat, oat, and rye production systems. The life cycle assessment showed that climate change impacts, on a production weighted average basis, were 79.6 kg CO_2 eq for wheat, 134 kg CO_2 eq for oats, and 116 kg CO_2 eq for rye. The negative emissions from soil organic carbon sequestration were not enough to make any of the crops grown under organic management net negative. This means that, although most individual farms were sequestering some soil organic carbon, and effectively offsetting a sizable portion of other GHGs being emitted in the production of the cereal crops, the organic farms were still net emitters.

The results of this analysis call into question the reliance of sustainable farming practices as a natural climate solution. Although this analysis only represents a small subset of Canadian organic farmers and it is not intended to be extrapolated to the entirety of Canadian organic growers, the results remain compelling. If future research reveals net organic farm emissions that are consistent with these findings, soil organic carbon sequestration will not be enough to fully mitigate against climate change impacts of agricultural production (Powlson et al., 2011; Amundson & Biardeau, 2018).

4.1 Contributions

Results from the Chapter 2 literature review will help life cycle assessment practitioners understand the current approaches to modelling soil organic carbon associated with the LCA methodology. Moreover, LCA practitioners will gain a better understanding of each model, its assumptions, its ability to simulate land management practices, and its use with modelling organic systems. These factors may help practitioners in choosing the best SOC modelling approach for their LCA study.

The life cycle assessment provided in Chapter 3 is the first life cycle assessment of Canadian organic field crop systems based on wide-spread primary data collection. Importantly, it also includes modeled soil organic carbon flux values. This analysis will provide benchmarking data for future studies to compare results to. Although the sample size was small, any data in this space is critical. Moreover, results of this chapter can help inform decision makers about climate change policy, since all systems were emitting emissions.

4.2 Conclusions

Climate change has become an increasing concern for Canadians. However, agriculture has been looked to as a climate change mitigation solution through sustainable farming practices such as those associated with organic agriculture. This thesis explores organic agriculture as a sustainable agriculture solution through assessing its net environmental impacts using the life cycle assessment methodology. The results of this analysis revealed that soil organic carbon sequestration does not offset all climate change impacts. However, given the locations and farm practices as modeled on the organic farms that provided data, the mostly positive increases in SOC on those farms meant that a considerable portion of other life cycle GHG emissions were offset. Nonetheless, the lack of net negative results suggests caution regarding the idea that organic agriculture should be relied on as a natural climate change mitigation solution. Moreover, as climate impacts of conventional wheat, oats, and rye agricultural practices and associated changes in SOC were not modeled in parallel, it is unknown what the difference in net emissions are as a function of organic management practices. Although the results are not meant to be extrapolated to broader Canadian geographies, the small sample size still shows the environmental impacts of a subset of Western Canadian farms. Future research is needed to determine if this subset of farms is representative of the national population of organic producers and the extent to which impacts arising from organic management differ from conventional practices for the same crops in a similar setting.

Future research should expand life cycle assessment studies in the organic space. Additionally, these studies should include soil organic carbon flux values and be based on widespread primary data collection. This research and its unique methodologies can help inform future studies in this space and provide baseline organic LCA data with SOC flux.

Planning for climate change mitigation has local, national, and global implications. Resting the burden of climate change mitigation solutions on the agricultural sector is unreliable, particularly considering the results of this thesis. It is recommended more research be done into the effectiveness of soil organic carbon sequestration as a climate change mitigation solution and how organic agriculture can play a role.

4.3 Future Research

In addition to the areas of future research already discussed throughout this thesis, further areas should include a combination of the main themes seen throughout the chapters: incorporating SOC with organic LCAs that rely on widespread primary data collection. The continued research in this area will provide a robust database to compare results with. Furthermore, continuing to build results in this area will help to confirm or deny a reliance on soil carbon sequestration as a climate change mitigation solution.

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APPENDIX A

Full list of papers reviewed in the SOC LCA literature review (Chapter 2)

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APPENDIX B

Table B-1. Results from a brief literature review of organic life cycle assessments of wheat, oats, and rye.

Title	**Author(s)**	**Year Published**	**Crop**	**Geography**	**Account for SOC?**	**Data Collection Method**
Determining the environmental and economic implications of lupin cultivation in wheat-based organic rotation systems in Galicia, Spain	Rebolledo-Leiva et al.	2022	Wheat	Spain	Yes	Field Experiment(s)
Would transitioning from conventional to organic oat grains production reduce environmental impacts? A LCA case study in North-East Canada	Viana et al.	2022	Oats	Canada	No	1 Survey / Questionnaire
Environmental life cycle assessment for improved management of agri-food companies: the case of organic whole-grain durum wheat pasta in Sicily	Zingale et al.	2022	Wheat	Italy	No	2 Surveys and Interviews
Evaluating the environmental profiles of winter wheat rotation systems under different management strategies	González-García et al.	2021	Wheat	Spain	Yes	Field Experiment(s)
Environmental Profile of Organic Dry Pasta	Cibelli et al.	2021	Wheat	Italy	No	Field Experiment(s)

Ecological challenges in life cycle assessment and carbon budget of organic and conventional agroecosystems: A case from Lithuania	Miksa et al.	2020	Oats Wheat	Lithuania	No	Field Experiment(s)
Environmental impacts of wheat-based vodka production using life cycle assessment	Bhattcharyya et al.	2019	Wheat	USA	No	1 Survey / Questionnaire
Contribution of old wheat varieties to climate change mitigation under contrasting managements and rainfed Mediterranean conditions	Carranza-Gallego et al.	2019	Wheat	Spain	Yes	Field Experiment(s)
Energy use and greenhouse gas emissions in organic and conventional grain crop production: Accounting for nutrient inflows	Hoffman et al.	2018	Wheat	USA	No	Field Experiment(s)
Influence of farming system on greenhouse gas emissions within cereal cultivation	Moudrỳ et al.	2018	Oats Rye Wheat	Czech Republic	No	Field Experiment(s)
Life cycle greenhouse gas emissions from integrated organic farming: A systems approach considering rotation cycles	Jeswani et al.	2018	Oats Rye Wheat	England	No	1 Survey / Questionnaire
The contribution to climate change of the organic versus conventional wheat farming: A case study on the carbon footprint of	Chiriacò et al.	2017	Wheat	Italy	No	2 Surveys / Questionnaire

wholemeal bread production in Italy						
Influence of farming systems on production of greenhouse gas emissions within cultivation of selected crops	Moudrỳ Jr. et al.	2013	Rye Wheat	Czech Republic	No	Unknown Number of Survey / Questionnaire
The emissions of greenhouse gases produced during growing and processing of wheat products in the Czech Republic	Moudrỳ Jr. et al.	2013	Wheat	Czech Republic	No	Unknown Number of Survey / Questionnaire
Comparing global warming potential, energy use and land use of organic, conventional and integrated winter wheat production	Tuomisto et al.	2012	Wheat	UK	No	Secondary Data
Evaluation of two production methods of Chilean wheat by life cycle assessment (LCA)	Huerta et al.	2012	Wheat	Chile	Yes	Field Experiment(s)

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APPENDIX C

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

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)?____

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

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							

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.

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**

Demographic Section: 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:

***formatting for each question is incomplete (proper MC format/a table/checkboxes)**

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
- Ph.D. 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
- Ph.D. or higher
- Degree wasn't in agriculture *
- Prefer not to answer

*drop-down options with different fields of study

  - 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

*drop-down options with different certification schemes indicated

- 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
    - 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
    - Education and/or other available information has informed my decision
    - I want to ensure that my farm can withstand drought, pests, invasive species, etc.
    - Farming is an enjoyable way of life
    - I consider myself a steward of the land
    - I have environmental concerns
    - Food quality is important to me

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

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
- Converting marginal crop land to perennial grass or trees
- Crop protection strategies

- Crop residue management
- Crop rotations and crop diversity
- Integrating livestock and crops
- Natural/non-chemical forms of fertilizer application
- Planting shrubs and trees as shelterbelts
- Reducing on farm fossil fuel usage
- Reducing fallow periods
- Reduction in tillage
- Restoring degraded land, improving pasture management
- Restoring wetlands
- Soil conservation strategies
- Using legumes and/or grasses in crop rotations
- Using rotational grazing and high-intensity/short-duration grazing
- Other
    - Not important at all
    - Slightly important
    - Important
    - Fairly important
    - Very important

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
- Converting marginal crop land to perennial grass or trees
- Crop protection strategies
- Crop residue management
- Crop rotations and crop diversity
- Integrating livestock and crops

- Natural/non-chemical forms of fertilizer application
- Planting shrubs and trees as shelterbelts
- Reducing on farm fossil fuel usage
- Reducing fallow periods
- Reduction in tillage
- Restoring degraded land, improving pasture management
- Restoring wetlands
- Soil conservation strategies
- Using legumes and/or grasses in crop rotations
- Using rotational grazing and high-intensity/short-duration grazing
- Other

Yes/No

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
- It provides me with economic advantages (e.g., premium price)
- I want to get ahead of government policy and environmental regulations
- Consumers are demanding low GHG emissions from their food
- Technological advancements make it easier (conservation practices, computer modelling, etc.)
- Other members of my family managing the farm emphasize its importance
- I have read research and/or received education or information that convinced me it is the right thing to do
- I am concerned about climate change
- I believe agriculture can help to substantially reduce global GHG emissions

- 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 to stay up to date with each of the following?

- New farming practices
- Agricultural policies and regulations
- Programs
- 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
- It costs too much
- I don’t have access to knowledge or training,
- I don’t have access to equipment and/or technical assistance
- I am not familiar with GHG reduction strategies

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

APPENDIX D

PARTICIPANT RECRUITMENT AND RETENTION IN AGRICULTURAL LIFE CYCLE ASSESSMENT STUDIES

D.1 Introduction

Participant recruitment is often a significant obstacle to research predicated on access to primary data held by individuals (Blanton et al., 2006; Leavens et al., 2018; Penckofer et al., 2011). Recruitment and retention of an appropriate number of participants is vital for study generalizability and validity in many studies (Visovsky & Morrison-Beed, 2012). Literature on participant recruitment strategies and successes is limited but primarily focuses on medical and health trials. For example, Gupta et al. (2015) highlight the use of technology and marketing techniques as successful means of recruiting large and diverse crowds of participants for clinical trials. Further, retention strategies such as study reminders and emphasizing the study benefits were correlated with increased participant retention in clinical research (Abshire et al., 2017). While some successful techniques in these studies may be transferable to recruitment strategies outside the medical field, there is a notable gap with respect to the availability of approaches for recruiting and retaining survey participants from the agricultural community. Moreover, the literature is particularly limited concerning recruitment of farmers and others involved in food systems for life cycle assessment (LCA) studies, where data collection surveys are frequently long and detailed, hence requiring a significant time commitment from participants.

D.1.1 Life Cycle Assessment

Environmental life cycle assessment (LCA) is a framework and methodology which adopts life cycle thinking to quantitatively assess and model the environmental performance of an industrial product system throughout the supply chain (Mazzi, 2020; Muralikrishna & Manickam, 2017; Yang et al., 2020). An LCA includes a detailed quantification of material and energy inputs and outputs of production systems (life cycle inventory, or LCI) and assessment of how those flows contribute to a range of global- to regional-scale resource depletion or environmental concerns. The International Standards Organization established ISO 14040 and 14044, to define general principles and specific requirements to conduct an LCA (ISO, 2016a, ISO, 2016b). 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, 2016).

Building the LCI requires robust and detailed data reflecting the inputs and outputs of a system to compute representative and accurate quantifications of environmental impacts. Data to build the LCI are collected from a variety of sources, which include databases such as census and statistical data, published values, and primary data collection (Bacenetti et al., 2016; Goglio et al., 2018; Knudsen et al., 2014; Pelletier et al., 2008; Tricase et al., 2016; Venkat, 2012). Primary data are typically collected through surveys and interviews, which can yield detailed respondent- and geographic-specific, current, and historical data. Primary data collection, from a range of sources, can provide substantial amounts of information and contribute to a representative model of a system. Therefore, understanding the challenges and most effective methods to recruit and retain participants for providing primary data is often crucial for conducting a robust LCA.

D.1.2 Recruitment Strategies for Agricultural LCA Studies

Agricultural LCAs have historically used a variety of methods for collecting data: from experiments, to secondary data, to interviews and surveys. However, few agricultural LCAs seek to characterize whole system types or geographies based on primary data. Therefore, the use of surveys on a large scale (>10 surveys) to gather life cycle inventory data is limited. A brief literature review of recently published (2010- June 2022) agricultural LCAs (n=50) revealed that only 14% of data collection methods included the use of surveys. Of those studies which employed a surveying method for data collection, only 29% of studies (n=2) surveyed more than 10 producers. The remaining studies from the literature review relied on methods such as interviews (n=4), experiments (n=19) and secondary sources (n=20) to provide LCI data.

As demonstrated by the small sample of literature, many agricultural LCA studies rely on case-specific data rather than seeking to characterize systems by crop or region. Studies that characterize systems more broadly often rely on secondary or regionalized information. For example, a 2008 study by Pelletier and colleagues characterized Canadian organic field crop production of canola, corn, soy, and wheat by obtaining LCI data from reputable secondary sources (e.g., national statistics), rather than sparsely available and often difficult-to-collect primary data (Pelletier et al., 2008). Obtaining robust on-farm data for context-representative characterization at such scales requires intensive and extensive recruitment of farmer participants. It has been shown that the recruitment process can be simplified using third-party survey distributors or dedicated survey mailing lists. A recent study by Bamber et al. (2020), for example, used a third-party recruiter for an LCA survey due to insufficient initial farmer engagement for the desired degree of characterization. However, such an approach can be costly, and mailing lists may not be available for producers who grow specific crops.

LCA is the most widely used tool for studying and managing environmental performance in food systems (Cucurachi et al., 2019), and its prevalence in the environmental literature is unparalleled. Yet, the most arduous aspect of many LCAs, the recruitment of participants for the collection of robust LCI data, is rarely discussed. Therefore, an in-depth analysis of survey recruitment and retention practices for agricultural LCAs would be highly beneficial for LCA practitioners. This study, therefore, seeks to understand the opportunities and challenges associated with recruiting agricultural producers for survey participation, in an LCA context.

D.2 Methods

The study was set in Canada and included recruitment efforts that spanned the ten provinces and three territories where organic producers and their contact information was publicly available (British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, New Brunswick, Newfoundland and Prince Edward Island, Nova Scotia, and Yukon).

D.2.1 Survey Design

The nature of life cycle assessments necessitates a quantitative research design and collection of a great deal of continuous (e.g., tonnes of manure applied to a field) and at times nominal (e.g., was the manure source from swine, poultry, or cattle) data types. Therefore, a survey that consisted of pre-determined and close-ended questions was used to collect both continuous numeric and associated nominal data on the cradle-to-farm gate production inputs and outputs associated with the growing of field crops in Canada under organic management. Participants were asked to provide relevant and complete data regarding their physical location (latitude, longitude, or legal land description), land-use practices (i.e. current and previous land management practices, certifications, and length under current management), crop inventory, nutrient and plant protection measures, irrigation inputs, field operation duration by types, post-harvest operations (grading, drying, cooling, and storage), and an optional close-ended questionnaire on respondents' demographics and management practices. For questions regarding participants' crop production practices, responses were recorded in labelled tables and fill-in-the-blanks that followed each question. The demographics questionnaire combined multiple choice, drop-down, and Likert scale style questions. In total, the survey consisted of twelve (with sub parts) crop production-related questions with sub-parts and seventeen optional demographics questionnaire questions (Appendix C).

D.2.2 Recruitment and Engagement Process

A formal database of organic field crop farmers across Canada does not currently exist. A potential list of participants was created from May to August of 2020 through repeated Google searches of organic field crop farms by province and more generally; contacting national and provincial agricultural organizations for access to their publicly accessible lists and to place recruitment ads in their newsletters, etc.; and requests to farmers themselves for potential leads and referrals (snowball sampling). Farmer contact detail information was assembled in a series of workbooks to track the following: farm province, address, email address, phone number, crops grown, farmer name(s), website, and contact attempts.

In advance of distributing the completed project survey, the second phase of recruitment efforts from May to August of 2021 involved circulating a 5-question screening survey (on the Qualtrics platform) with a cover letter (~3-5 minutes) to all identified organic field crop farmers for whom there was an e-mail address. In addition, ads alerting the organic farming community to the existence of the recruitment survey were distributed via newsletters and mailing lists by agricultural organizations that agreed to provide assistance. This initial screening and recruitment included questions about farm location, crops grown, and overall interest in being contacted to participate in the study and receive the entire survey. Those farmers that responded with interest in providing data to the project were then contacted by phone or email to confirm interest and determine their preferred method of survey completion. Use of the screening survey was discontinued by November of 2021, marking the end of the participant recruitment period, after which individuals who indicated interest in sharing data only received the entire survey.

To increase the number of surveys returned, the following approaches were used.

Contacting Participants Directly

Survey participant recruitment efforts occurred from May to November of 2021. During this period, the Coronavirus pandemic and its associated public health measures restricted travel and safe in-person meeting opportunities across Canada. Moreover, as our early efforts to recruit participants via the screening survey were far poorer than hoped, we resolved to try and communicate with every organic farmer for whom we had previously assembled contact information. This personal outreach work was led primarily by a bilingual (English-French) research assistant that was hired specifically for this effort. Where phone numbers were available for farmers, this means of contacting was used first, unless otherwise indicated by the farmer. Where only e-mail addresses were available, these were used as the primary basis of contacting farmers during this phase. Farmers were contacted to request their participation in the complete survey that would take approximately one to three hours to complete, depending on data availability and farm operation size. Efforts were made to contact all farmers for whom we had one or another form of contact information a maximum of three times, except those who agreed to be contacted further. Following the first unsuccessful contact attempt (e.g., phone call was not answered, e-mail was not responded to), a two-week waiting period took place before attempting to re-contact the farmer a second time. Finally, if there was no response the second time, an additional two-week waiting period took place before the final contact attempt was made. Participants contacted via phone were left a voicemail if that option was available. Farmers who answered 'maybe' to participating in the survey were only contacted again if they requested a follow-up at an agreed-upon date.

Using Organic Associations and Networks

Several provincial and national agricultural organizations (n=24) were contacted to increase survey recruitment efforts. They agreed to advertise the survey via their newsletters, email lists, websites, and social media platforms either bi-weekly or monthly. In addition, 'champions' and 'influencers' in the agricultural sector were identified (n=20) to help raise awareness of the study and its importance and increase survey engagement within their networks. Industrial firms with a strong dependence on organic agriculture production, such as breweries, milling and snack companies (n=6), were contacted for their support and potential completion of our survey where those same companies either produced or have management control over organic crop production. In addition, these firms were also asked to provide their growers' contact information. Follow up contact was then made with these organic farmers. Lastly, social media platforms were searched to identify designated organic farming Facebook and LinkedIn groups (n=4). Moderators of these groups were contacted and when permission was granted, details of the study and the associated screening survey were distributed to the membership of these Facebook groups.

Remuneration

Initially, farmers were not offered remuneration for time spent completing our larger inventory survey. This was because principal funding for this research stipulated that farmers also ‘invest’ in the research through either nominal cash or in-kind contributions, where the latter could take the form of time spent providing data. However, after 18 months of farmer recruitment efforts yielded only seven complete inventory surveys, permission was sought and granted to offer farmers a $50 remuneration for each completed survey associated with growing one crop under organic management. Consequently, participants who submitted multiple complete surveys for their additional crops grown under organic management could receive $50 for each completed survey. Remuneration was retrospectively extended to those participants who completed and submitted the survey before compensation was introduced. Once remuneration was approved, this new information was used as a basis for re-contacting individual farmers who had previously expressed a willingness to provide data via the methods described above.

D.2.3 Data Collection Procedures

Prospective participants were offered three approaches to completing the survey if they agreed to receive the entire survey. Moreover, participants who agreed to complete the survey also agreed to be contacted further if they had questions or their responses required clarification by members of the project team. The survey was published online through a secure link available through the survey software application, REDCap (Research Electronic Data Capture). In addition, potential participants were also given the option to receive a hard copy of the survey by mail, or to fill out the survey in real time with a researcher via video or phone call. All three approaches were available in both English and French. As public health measures were eased, prospective participants were offered in-person meetings to help complete the survey, but no farmer elected for this option. The following provides details for each approach.

Telephone approach: A researcher and potential participant discussed a mutually agreed-upon date and time if the survey was to be completed over the phone. The researcher would begin a new REDCap survey, request consent for participation in the respondent's preferred language, pose questions as written, and fill in the survey electronically on behalf of the farmer-respondent.

Mailed approach: Hardcopy surveys were also made available to participants when requested. The package included an information and appreciation letter, consent form, survey package, addressed envelope, and stamp. Once the survey package was initially mailed, participants were informed via phone or email. Participants received a follow-up call or email if the survey was not returned within three to four weeks. Once completed, participants could repackage and return the survey to the researcher.

Electronic Approach: Participants who requested digital access to the survey received a secure unique link to the REDCap application. Participants were informed that answers could be saved if they decided to complete the survey over multiple visits to the website. The REDCap software also kept track of survey progress and responses. Researchers could track whether participants opened the survey, the state of progress made by respondents, and which surveys were incomplete or complete. Reminders were sent periodically via email or phone (every two weeks until the survey closed) if a survey was only opened or left incomplete. If incomplete, participants were also offered an invitation to complete the survey with a researcher support via either an in-person or digital meeting considering public health measures prevailing at the time.

D.2.4 Data Storage, Tracking, and Analysis

Given the large number of organic farmers to contact, and as participant recruitment activities were undertaken by up to four individuals working at times in parallel, there was a need to formally record each individual farmer recruitment event and its outcome. This was done using a cloud-based spreadsheet workbook (Microsoft Excel for OneDrive) in which farmer contact information, organized by province, and all related contacting effort and outcome activities was recorded to ensure organization and documentation throughout the recruitment process. The spreadsheet included details such as the method(s) used to contact the participant, the date the participant responded, dates of subsequent contact attempts and the method(s), their stated willingness to complete the survey, the mode of survey they wish to complete, survey progress (i.e., incomplete, complete, and completion date), and details regarding their remuneration status. This information formed the basis for the statistical analyses of this study's recruitment efforts. Results will be presented descriptively and analytically using statistics, charts and diagrams.

D.3 Results

The results are presented as follows: an overview of the study population, recruitment methods and retention successes, participant responses to recruitment attempts, and participant interaction with the online survey.

D.3.1 Respondent Sociodemographic Characteristics

As outlined in Section 3.2, several optional demographic questions were included in the survey. In total, 46 of the 50 survey respondents provided answers to the demographic questions. (Figure D.1).

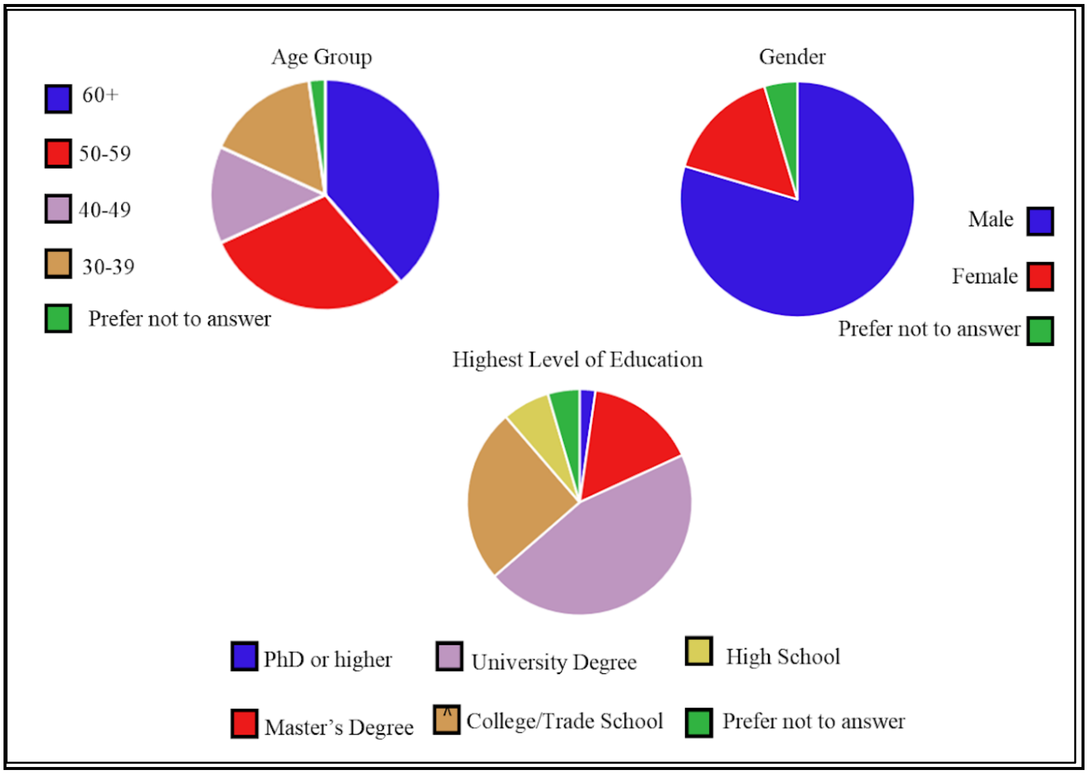

Figure D-1. Sociodemographic characteristics (i.e., age, gender, and the highest level of education) of participants who completed the agricultural LCI survey

Participants who completed the survey and opted to provide demographic information revealed that largest age group represented (39%) were 60 years old or above, with the next highest contributing age group being 50-59 years old (30% of participants). The demographic information further showed that respondents were mostly (80%) male. Lastly, a look at participants' highest level of education indicates 2% of participants reported holding a Ph.D. or higher, 16% had earned a Master's degree, 45% of participants had completed a University degree, 25% went to college or trade school, and 7% had earned a high school diploma (Figure D-1).

D.3.2 Recruitment Methods and Retention Success

In total, 683 organic farmer participants were identified and contacted. Of the 683 prospective participants, 37% (253) were from Quebec (QC), 15% (101) from Ontario (ON), 7% (49) from Prince Edward Island (PEI), 3% (20) from Nova Scotia (NS), 3% (20) from the Yukon (YT), 3% (18) from New Brunswick (NB), 1% (9) from Newfoundland and Labrador (NL), 14% (99) from Alberta (AB), 7% (47) from Saskatchewan (SK), 6% (38) from Manitoba (MB), and 4% (29) from British Columbia (BC) (Figure D-2).

Of the 683 potential participants, 170 (25%) did not respond to any form of recruitment method regardless of the number of attempts made to contact them (Figure D-2). Almost half (48% or n=332) of potential participants declined participation or were ineligible (i.e., were no longer farming under organic management, were not growing field crops, etc.) (Figure D-2). Only 4% (n=29) of potential participants indicated that they would 'maybe' be interested in participating, while 23% (n=143) indicated that they would like to participate and were provided with access to a survey in their preferred form (Figure D-2).

Ultimately, only 7% (n=50) of the original 683 potential participants with whom we attempted contact completed one or more crop-specific surveys (Figure D-2). Furthermore, this indicates a 34% retention rate of participants who indicated that they would complete a survey (n=148) and then went on to do so (n=50). Participant retention refers to participants who continued to participate through the entire survey process, from recruitment to survey completion.

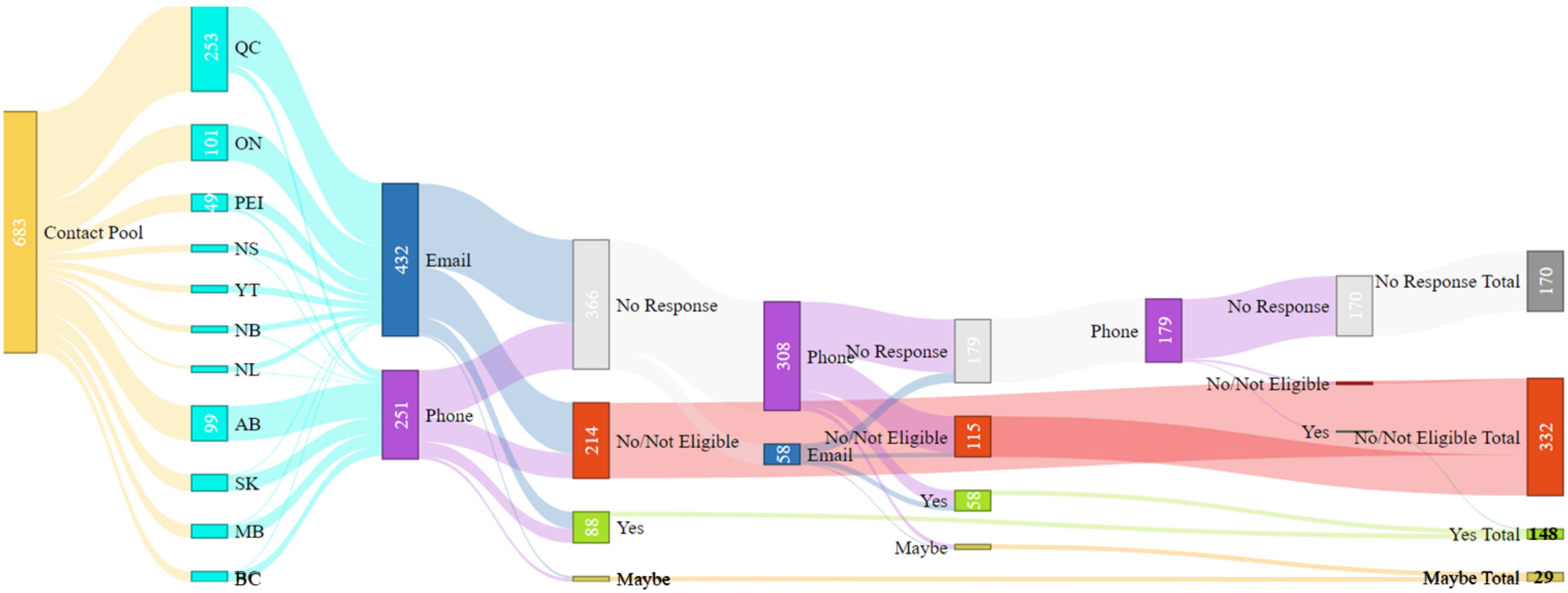

Figure D-2. Participant recruitment by province; recruitment attempts by method (i.e., phone or email); participant response with each recruitment attempt; and overall participant retention.

Participant retention also varied by province, with the most successful retention occurring in Saskatchewan where fully 26% (n=12) of 47 potential participants that we attempted to contact in that province, ultimately completed surveys. Other provincial participant retention rates, relative to the original number of potential organic farmers for whom we had contact information, are as follows (in declining order of retention): Ontario: 17%; British Columbia: 14%; Manitoba: 8%; Alberta: 6%; New Brunswick: 6%; Nova Scotia: 5%; Quebec: 2%; Newfoundland and Labrador: 0%; Prince Edward Island: 0%; and Yukon: 0%.

Importantly, as respondents were able to complete inventory surveys for more than one of their crops grown in rotation, the 50 farmer respondents combined to provide data on 144 field crops grown under organic management resulting in a total of $4,000 paid to farmers as remuneration for their time. Notably, the total is $4,000 instead of $7,200 (i.e., $50 per crop) since many farmer declined payment or never returned our contact attempts for confirmation of address and permission to send the remuneration. Of the 144 completed crop-specific surveys submitted, 91% (n=73) were provided after remuneration was offered to farmers.

D.3.3 Participant Responses to Recruiting Attempts

Responses to every recruitment activity (i.e., phone call made or e-mail sent) were categorized as 'No response', 'Maybe', 'No/Not eligible', and 'Yes'. Figure D-3 illustrates the variation of responses associated with each of three recruiting attempts.

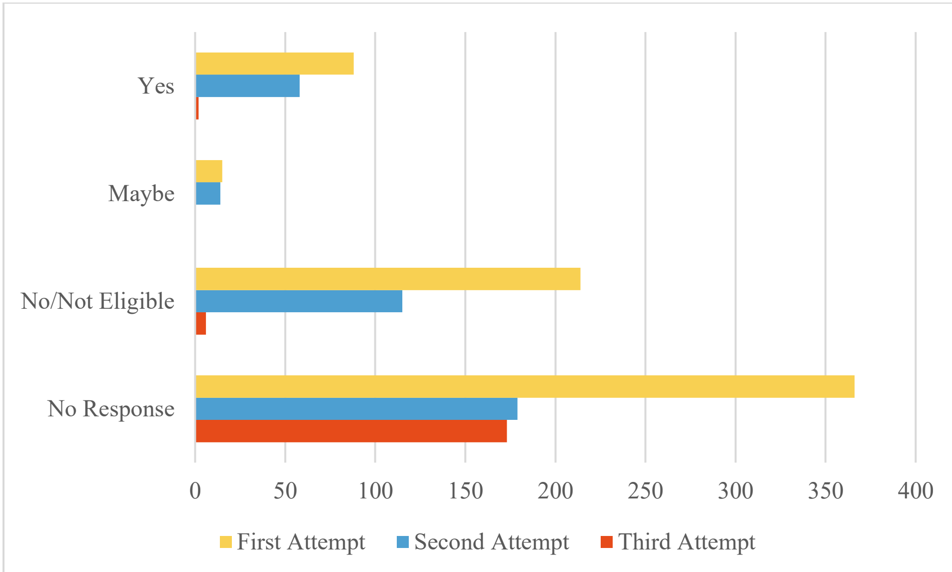

Figure 19. Participant responses to first, second, and third recruiting attempts by the research team categorized by the response: ‘no response’, ‘maybe’, ‘no/not eligible’, and ‘yes’

The first recruiting attempt resulted in the largest number (n=366) and highest percentage (54%) of 'No response', while 31% (n=214) of those initially contacted said they did not want to participate or were ineligible. Participants indicated 'Yes' they would complete a survey 13% of the time during the first contacting attempts, and 2% indicated 'Maybe' during the first contacting attempts (Figure D-3).

The second recruiting attempt yielded 'No response', 'No/Not eligible', 'Yes', and 'Maybe' at 50%, 32%, 16%, and 2%, respectively. The third and final recruiting attempt yielded 'No response', 'No/Not eligible', 'Yes', and 'Maybe', 96%, 3%, 1%, and 0%, respectively (Figure D-3).

D.3.4 Participant Interaction with the Online Survey

The experience with the specific mode of survey (e.g., online, hard copy, over the phone) may have been an important factor in whether a farmer ultimately filled out a survey or not. Most participants who indicated a willingness to complete a survey opted for the online electronic version instead of a hard-copy mailed or a telephone walk-through. Figure D-4 illustrates the final status of individual farmer interactions with the online survey. In total, 320 participants interacted with the digital survey to some extent.

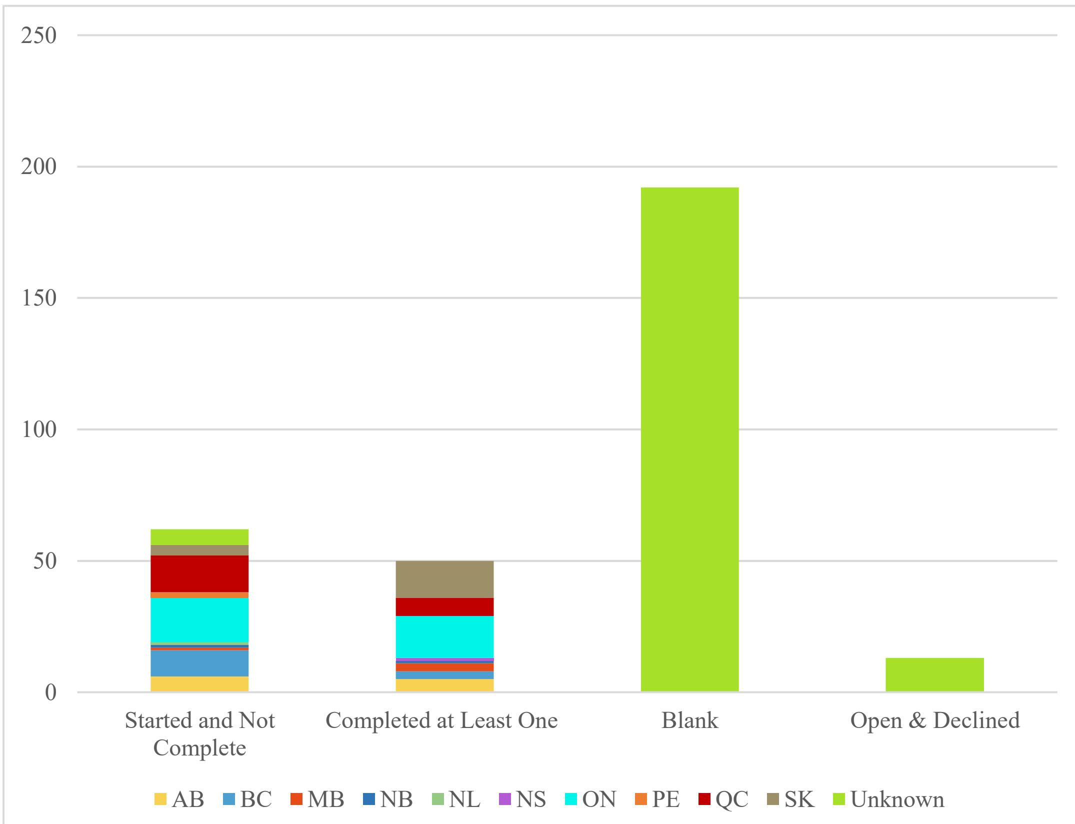

Figure D-4. Participant interaction with the online survey. 'Started' indicates a survey that was neither completed nor blank. 'Open & Declined' refers to open surveys, but respondents declined to participate or were ineligible to participate because they did not grow field crops.

Of the interactions with the online survey, 20% were started but ultimately never completed. Blank surveys accounted for 60% of survey interaction (Figure D-4). Finally, 16% of online surveys were completed, meaning all completed surveys were done so through the online method (some with the help of a researcher over the phone).

Far fewer surveys were distributed as hard copies by mail (n=13), and none were returned. There were 11 fully completed with the assistance of one of the researchers over the phone.

D.4 Discussion

This study was aimed at understanding the opportunities and challenges associated with recruiting agricultural producers for survey participation, in an LCA context, to collect robust life cycle inventory data for a life cycle assessment study of Canadian organic field cropping systems.

Overall, despite a large effort, with four research assistants, to contact, recruit and engage farmers, data were only collected from 50 farmers, even though 683 organic field crop farmers were identified and contacted for potential participation. The response rate was 7%, which is typical for businesses (Savad, 2021), but unknown for the agricultural LCA context. The following discussion outlines some of the factors that affected participation, based on researchers' observations of the process and feedback from producers.

D.4.1 Barriers to Participation

Coronavirus Pandemic: The farmer recruitment process began in May 2020 and finished in February 2022. This process occurred during most of the major COVID-19 outbreak 'waves', which resulted in public health-mandated lockdowns in Canada. As a result, farmer recruitment and data collection approaches were often adjusted throughout this process, due to the continually shifting federal and provincial restrictions related to managing the Coronavirus pandemic. By September 2021, restrictions in most parts of Canada no longer formally limited our ability to meet with farmers; however, participants continued to decline in-person meetings for the remainder of the recruitment and data collection period for unknown reasons (i.e., potentially because of continuing Coronavirus concerns, lack of interest in the study, lack of time to meet, etc.,). Instead, they opted to complete the survey remotely (via the online platform, or through a call with a researcher). Several farmers, who had signaled a willingness to complete the survey, reported that they struggled to complete it, because of a lack of time (potentially also related to survey design and length, discussed below), increased stress, or financial constraints, all related to the pandemic. This is consistent with other observations that producers were faced with compounding stress during this time from economic hardships and supply chain issues (Pappas, 2020).

Survey Design and Length: Informal feedback from participants regarding the survey included concern regarding its length and level of detail. Our survey was 84 questions (including sub questions) per crop in rotation. Despite concerns expressed regarding the time required to complete our survey, its form and detail was retained to ensure that we had the high-quality foreground system inventory data required for a robust LCA study. Additionally, unlike other types of surveys, which might ask for opinions, producers had to take time, and likely look up records to obtain the quantitative data required. As reported in Saleh and Bista (2017), participants are more likely to "complete the survey if it takes less than 15 minutes" (p. 70). Therefore, keep surveys as short and as simple as possible, using language that is familiar to the sector. Even when lengthy, a survey designed to elicit LCA data should be easy to access and complete, non intimidating, and user-friendly, especially when the survey will be completed online or in hard copy without direct support of a researcher (Brosnan et al., 2019; Fan & Yan, 2010; Couper, 2000). A few design features recommended for an LCI data collection survey include a progress bar and a 'save' function. When completing a hard-copy survey, participants can simply flip through its pages to gauge the length of the survey and their progress. In retrospect, a potential flaw of the organic field crop survey that may have contributed to participant fatigue was the amount of manual input required by participants when disclosing their LCI data (Appendix C). For example, participants were asked to type names of inputs, how some were applied, crops produced, etc. This could have been simplified for users by including 'drop-down' options wherever possible (e.g., crop types, units, nutrient application types). This approach, however, does require a high degree of foreknowledge regarding many possible inputs or the inclusion of 'other' options and the ability for users to add items. Last, to reduce the potential of inadvertent non-response related to questions for which all respondents should be able to provide a non-zero/blank answer (e.g., farm location, area of crop seeded, crop yield, etc.), including 'required questions' that must be completed to move on is recommended (Loomis & Paterson, 2018). A user-friendly and accessible survey design has a greater potential to yield higher quality data and more completed surveys.

Survey Fatigue: Producers mentioned survey fatigue due to the many surveys circulating in the organic sector or amongst farmers in general around the same time. In conversations we had with associations, they mentioned they were also surveying farmers.

Access to Producers' Contact Information: At the outset of farmer recruitment, we were confronted by the lack of any systematic list of database of organic farmers, either nationally or provincially. Consequently, our ability to connect with farmers was limited to indirect means (e.g., outreach via newsletters and websites) or directly via the assembly of farmer name and contact information gleaned from publicly accessible sources. These contact data, however, are not just incomplete but potentially inaccurate and outdated. Amongst the 683 farmers for whom contact data were assembled, there were many retired farmers, inactive farms, and, in some cases, contact information that was for the wrong person. In other instances, phone numbers were out of service, or email addresses were no longer valid. Even when contact details were correct, it is possible that some emails landed in the ‘spam’ folders while some apparently active phone numbers did not then allow voicemail messages.

D.4.2 Drivers for Participation

Online Survey: All of the farmers (n=50) completed the survey using the online format. This is consistent with findings that online surveys are both effective and feasible for hard-to-reach or unique populations (Regmi et al., 2016; Wright, 2005), as is the case for organic farmers in Canada, whose schedules are highly variable and often work long hours during the planting and harvesting seasons. Additionally, online surveys are effective from a researcher’s point of view, as they can reach large populations across spatial-temporal scopes, can be used to collect large amounts of data, and are cost-effective (Regmi et al., 2016; Wright, 2005), and are time-saving for both respondents and researchers (Wright, 2005). For an online survey, including an indicator of progress may increase the likelihood of participants completing the survey (Yentes et al., 2012). In their review survey enjoyment and focus and the effect survey progress bars play on those factors, Yentes and colleagues (2012) concluded that including a progress bar increased data quality through increased focus demonstrated by the survey respondents. If participants choose to complete an online survey on their own, it is also recommended that participants are able to save their incremental responses and access the survey at a later date. Disclosing details such as a 'save' function is another strategy to increase participants’ willingness to expend their time over more than one sitting.

Researcher Walkthroughs: Producers who worked with one of the researchers completed the survey. It has been found that having someone helping the respondent can reduce participants’ perceived effort and task difficulty, and creates a sense of shared commitment (Heerwegh & Loosveldt, 2008). A well-trained surveyor that is comfortable with the survey material can explain unclear terms, provide motivation, reassure confidentiality, probe incomplete or inadequate responses, and reduce item nonresponse compared to web survey respondents (Couper, 2000). One theoretical approach that explains this phenomenon in survey participation is the satisficing theory which assumes optimal responses to questions require a substantial amount of cognitive effort (Krosnick et al., 1996; Heerwegh & Loosveldt, 2008). A face-to-face survey experience can motivate respondents to better interpret questions, respond thoughtfully, draw on relevant memories, and report their responses thoroughly, while web-based surveys lack nonverbal communication that may allow respondents to make cognitive shortcuts and exhibit reduced effort (Heerwegh & Loosveldt, 2008; Krosnick et al., 1996). Therefore, scheduling a phone or video call or face-to-face meeting with potential surveyees and those that have submitted incomplete surveys can increase a surveyee's willingness to complete the survey following a real-time conversation with a researcher. It is a valuable opportunity for participants to ask questions, learn more about the project they have agreed to participate in, and thus, feel more committed to completing the survey.

Remuneration: Remuneration was introduced to compensate for the time and effort taken by participants to complete the survey. Though it is impossible to know the specific benefit of compensating farmers for their time, particularly as some farmers informally indicated that it was a matter of time availability and interest, not compensation that influenced their survey completion, before the compensation was offered we had secured just seven completed surveys. After compensation was offered, we managed to secure an additional 43 surveys from farmers. Importantly, older respondents are more likely to complete the survey if remuneration is offered (Saleh and Bista, 2017), which is consistent with our study population where 69% of respondents were over the age of 50.

Survey Reminders: Throughout the survey period, several reminders were sent to participants about completing the survey. Those who completed surveys were mostly (80%) male. This is consistent with Saleh and Bista (2017) who found that males may be more likely to complete surveys if they receive reminders. However, the actual benefit of survey reminders in this analysis are unknown. Nonetheless, regular follow-ups were an essential and perhaps initially underappreciated part of the retention process. When an online survey remained incomplete, follow-up emails were sent bi-weekly and respectfully asked if participants had questions, preferred a phone call to discuss the survey, and included another copy of the survey link. Most often, these follow-up emails prompted participants to either start the survey or work on completing it. Based on this experience, it is recommended that surveyors utilize strategies such as email and Short Message Service (SMS) notifications to yield a higher response rate (Fan & Yan, 2010; Bosnjak & Tuten, 2001). Furthermore, a review by Fan & Yan (2010) emphasize sending personalized survey invitations and including a deadline for survey participation as additional tactics to increase response rates for both hard-copy and web-based surveys.

Using Organic Associations and Networks: While direct results of reaching out to organic associations and networks are unknown, the literature suggests that participants are more likely to complete surveys if they hear about it through a reputable person or organization in that field (i.e., and organic association or their organically-farming neighbor) (Saleh and Bista, 2017). A 2017 study by Saleh and Bista suggests that reaching out to major organizations in the field of interest to help distribute surveys will result in more completed surveys. Similarly, prior research suggests that surveys sponsored by academic and government-based institutions are more likely to receive higher response rates than commercially sponsored surveys (Fan & Yan, 2010). Therefore, including academic institution logos and other identifiers and listing any government affiliations are recommended. Experts such as extension officers, ‘champions’, and ‘influencers’ are another set of individuals that can, in theory, increase survey engagement when they are actively engaged with the objectives of the research. The term ‘champion’ emerged from innovation-based literature to define a passionate individual and a strong advocate for products and projects, “and generates positive behavioural support for an innovation during its development or work on behalf of the project” (Mumford & Harvey, 2014, p. 497; Markham et al., 1991). In the agricultural context, these individuals are often well-known in their communities, have extensive networks and contacts, and can ‘champion’ or ‘influence’ increased participation in research endeavours through marketing on the researchers’ behalf and completing the survey themselves. However, identifying these individuals and winning them over to the research enterprise can be challenging.

Participant Education Level: Where our respondents differ markedly from the national population of farm operators is in regard to formal education attainment. While only 17% of the national farm operator population had earned a university degree at the bachelor’s level or above (Statistics Canada, 2011), 63% of our respondents who completed surveys had obtained a degree at the bachelor’s level or above (Figure D-1). What we do not know, however, is the rate of university degree holding amongst organic farm operators in Canada. It is possible that this sub-population of farmers has complete formal tertiary education at rates closer to our sample of survey respondents. Prior research does suggest, however, that higher levels of educational attainment does correlate with higher survey completion rates. For example, Jang and Vorderstrasse (2019), who studied web-based survey participation in parents of preschool children, found that less-educated participants “were less likely to complete the survey compared with their counterparts with more education” (p. 1). Similarly, Turrell et al. (2007) who looked at food purchasing behavior in various Australian socio-economic positions concluded that less-educated individuals are less likely to be successfully recruited for survey participation and retained through survey completion. However, the high levels of education could be explained by a correlation between subject interest and survey completion. Saleh and Bista (2017) studied factors that impact online survey response rate in educational research and they conclude that participants are more likely to complete a survey if they are interested in the topic. This is consistent with our analysis, particularly where 59% of respondents indicated earning their post-secondary education in agriculture.

D.4.3 Comparison to Agricultural LCA of Peas and Lentils

A recent, parallel agricultural LCA study by Bamber and colleagues (2020) provides another perspective on strategies for farmer recruitment and inventory data collection. In their work, Bamber and colleagues (2020) sought to characterize the environmental performance of large-scale conventional pulse cropping systems in Canada. Initially, they attempted to recruit farmer participants to their project by advertising their survey to farmers through a major industry organization (i.e., Pulse Canada), who were also the sponsors of the research. They initially also offered participants the chance to win a $1,000 Amazon gift card. This approach, however, did not gain sufficient traction and resulted in only 92 completed surveys. As this was far short of the desired level of data collection, Bamber and colleagues changed strategy and hired a third-party for-profit surveying company with extensive links in the Canadian agricultural sector. This third-party contacted and distributed the survey to a pool of farmers already established with the company, and then paid each farmer who completed the survey an undisclosed sum. This intervention resulted in a 504% increase in survey participants: from the initial 92 complete surveys prior to the intervention to an additional 464 completed surveys. While hiring a third-party surveying company may be a costly endeavour, the results from Bamber et al. (2020) demonstrate its value in that study's context, particularly when inventory data are sought from a large number of producers who are already connected to one or another of these private survey companies. Similar to Bamber and colleagues (2020), the organic farmer recruitment and survey completion efforts outlined here opted to offer remuneration when initial recruitment and survey completion rates fell short of expectations. Once we provided a nominal $50 remuneration payment to farmers, this increased engagement substantially. Even with financial compensation offered is small, it can be a way to show appreciation for the participant's time and effort (Permuth-Wey and Borenstein et al., 2009) and it has been shown in other scenarios to effectively increase participation (Cho et al., 2013; Kauffman et al., 2008; Mason and Watts, 2009). It should be noted that remuneration was introduced at the same time the bilingual research assistant, who was dedicated solely to contacting farmers, was hired. Therefore, the increase in participation after introduction of remuneration may also be attributed to the shift in contacting approach: making it more streamlined and dedicating more time to it.

Based on informal feedback provided by a few farmers, for some, remuneration was not a significant factor in their decision to complete the survey, but rather an issue of time. Furthermore, a small fraction of participants decided to donate their remuneration to other organizations. In most cases, however, remuneration was well-received and appreciated, and importantly, it appeared to substantially increase organic farmer engagement with our survey. What is unclear though is whether it was the amount of money offered that ultimately attracted participants or that the introduction of remuneration many months after recruitment efforts started provided an opportunity for researchers to re-engage potential participants. Despite this uncertainty, it is recommended that remuneration is offered at the onset of survey advertising to optimize time and engage potential participants as early as possible. In consideration of participants' time and effort required to complete a typical, detailed life cycle inventory survey, remuneration appears to be the most effective strategy in the absence of other motives to participate (Singer & Kulka, 2002). By introducing remuneration as early as possible in the process, researchers can ensure the greater inclusion of potential participants and avoid re-contacting potential participants to inform them of remuneration.

D.4.4 Recommendations

To increase producer participation in surveys for LCI data collection, the following strategies should be used:

1) Use a survey service
2) Remuneration
3) Use online surveys
4) Keep surveys as short and as simple as possible
5) Provide guidance on time and material required for survey completion
6) Offer to meet or talk through the survey with the potential participant
7) Use Snowball sampling, networks, and influencers to encourage responses
8) Follow up with potential participants

D.5 Conclusion

The success of many research projects hinges on the successful recruitment and retention of participants. Environmental life cycle assessment studies require strong participant engagement for robust data and accurate results. In our work, 683 potential participants were identified and contacted to participate in a survey designed to determine the net greenhouse gas emissions and life cycle environmental impacts of organic field crop production in Canada. Contacting was executed by email, phone calls, and mail, and ultimately resulted in 50 respondents completing one or more surveys for an overall response rate of 7% (recall that these 50 respondents though ultimately provided inventory data related to 144 total Canadian farm-field crop combinations). Various barriers to participation were identified such as the Coronavirus pandemic, the survey design and length, survey fatigue, or access to accurate producer contact information. Additionally, drivers to participation were uncovered including the use of the online survey, researcher walkthroughs, remuneration, survey reminders, reaching out to organic organizations and networks, and participant education level. The survey recruitment strategies and response rate of this analysis were compared to that of Bamber et al. (2020). Ultimately, seven recommendations resulted in hopes that future agricultural life cycle assessment practitioners can collect robust life cycle inventory data, drawing on the recruitment strategies tested in this study.

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APPENDIX E

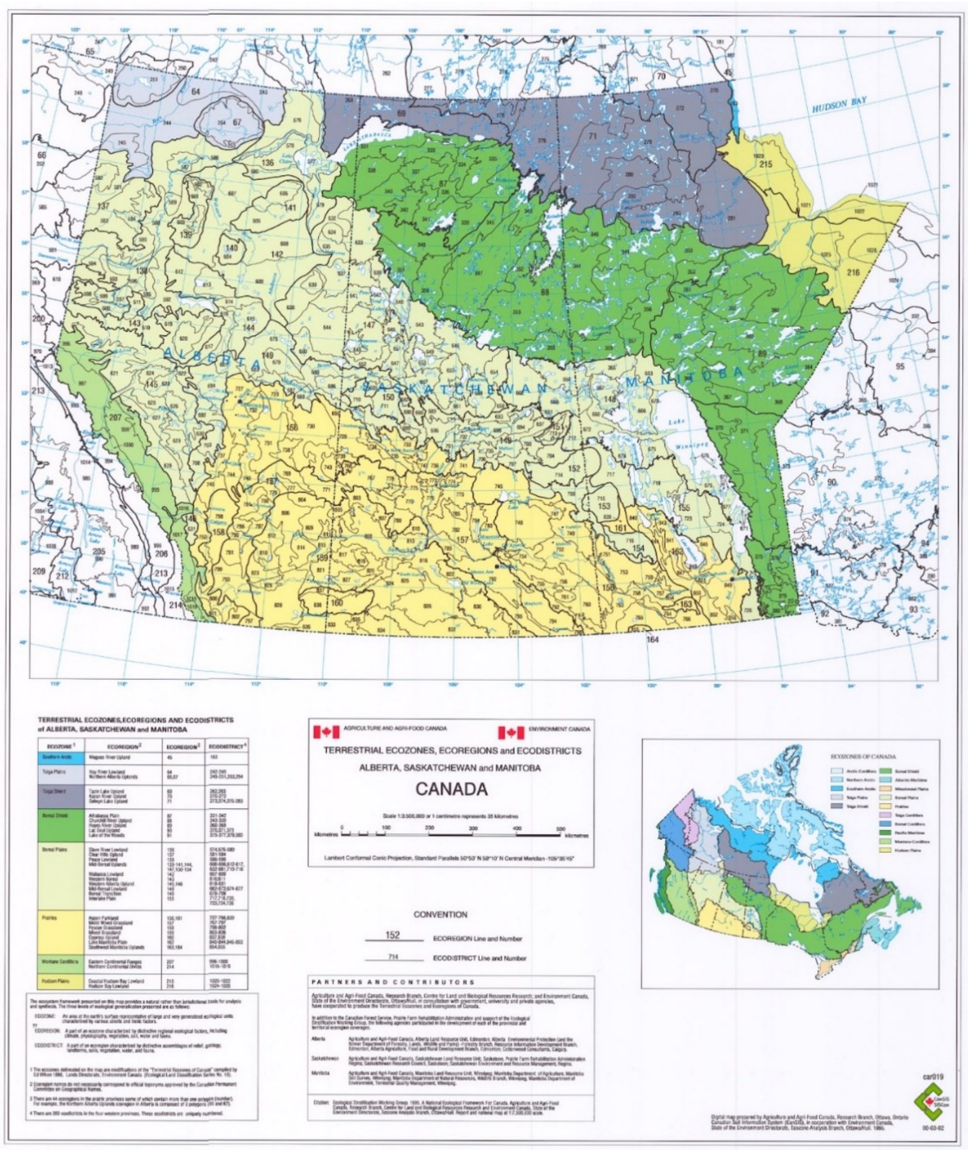

Figure E-1. Map of the terrestrial ecozones, ecoregions and ecodistricts of Alberta, Saskatchewan, and Quebec (Ecological Stratification Working Group, 1995).

APPENDIX F

Table F-1. OpenLCA process modifications for location-specific granularity

Process	Modification
ammonia production, partial oxidation, liquid | ammonia, anhydrous, liquid |APOS, U - CA	Prairie-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, AB	Provincial-specific location; Provincial-specific provider for electricity, low voltage; Canadian-specific heat, district or industrial, natural gas
ammonium nitrate production | ammonium nitrate | APOS, U - CA, MB	Provincial-specific location; Provincial-specific provider for electricity, low voltage; Canadian-specific heat, district or industrial, natural gas
ammonium nitrate production | ammonium nitrate | APOS, U - CA, SK	Canadian-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	Canadian-specific location; Rest-of-North-America provider for ammonia, anhydrous, liquid; Provincial-specific provider for electricity, medium voltage
ammonium sulfate production | ammonium sulfate | APOS, U - CA, AB	Provincial-specific location; Rest-of-North-America provider for ammonia, anhydrous, liquid; Provincial-specific provider for electricity, medium voltage

calcium ammonia nitrate production | calcium ammonium nitrate | APOS, U - CA	Canadian-specific location; Provincial-specific provider for electricity, low voltage
calcium ammonia nitrate production | calcium ammonium nitrate | APOS, U - CA, AB	Provincial-specific location; Provincial-specific provider for electricity, low voltage
calcium ammonia nitrate production | calcium ammonium nitrate | APOS, U - CA, MB	Provincial-specific location; Provincial-specific provider for electricity, low voltage
calcium carbonate production, precipitated | calcium carbonate, precipitated | APOS, U -CA	Canadian-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; Canadian-specific provider for water, decarbonised
clover seed production, Swiss integrated production, for sowing | clover seed, Swiss integrated production, for sowing | APOS, U - CA	Canadian-specific location; Provincial-specific provider for electricity, low voltage
fishmeal and fish oil production; 63-65% protein, from fish residues | fishmeal, 63-65% protein | APOS, U - CA	Canadian-specific location; Provincial-specific provider for electricity, medium voltage; Canadian-specific provider for heat, district or industrial, other than natural gas
lentil seed production, for sowing | lentil seed, for sowing | APOS, U - CA	Canadian-specific location; Provincial-specific provider for electricity, low voltage; Provincial-specific provider for lentil
market for protein pea, organic | protein pea | APOS, U - CA	Canada-specific location; Canadian-specific provider for protein pea, organic

market for wheat grain, organic | wheat grain, organic | APOS, U - CA	Canadian-specific location; Canadian-specific provider for wheat grain, organic
oat seed production, Swiss integrated production, at farm | oat seed, Swiss integrated production, at farm | APOS, U - CA	Canadian-specific location; Canadian-specific provider for ammonium nitrate; Canadian specific provider for application of plant protection; Canadian-specific provider for combine harvesting; Rest-of-world provider for drying of bread grain, seed and legume; Canadian-specific provider for fertilising by broadcaster; Canadian-specific provider for inorganic nitrogen fertiliser, as N; Canadian-specific provider for inorganic phosphorous fertiliser, as P2O5; Canadian-specific provider for liquid manure spreading, by vacuum tanker; Canadian-specific provider for oat seed, for sowing; US-specific provider for market for phosphate rock, beneficiated; Canadian-specific provider for solid manure loading and spreading, by hydrauling loader and spreader; Canadian-specific provider for sowing; Canadian-specific provider for tillage, cultivating, chiselling; Rest-of-World provider for tillage, currying, by weeder; Rest-of-World provider for tillage, harrowing, by spring tine harrow; Canadian-specific provider for tillage, ploughing; Rest-of-World provider for transport, tractor and trailer, agricultural; Rest-of-North-America provider for market for urea production
oat seed production, for sowing | oat seed, for sowing | APOS, U - CA	Canadian-specific location; Provincial-specific provider for electricity, low voltage
oat seed production, for sowing | oat seed, for sowing | APOS, U - CA, AB	Provincial-specific location; Provincial-specific provider for electricity, low voltage
oat seed production, for sowing | oat seed, for sowing | APOS, U - CA, MB	Provincial-specific location; Provincial-specific provider for electricity, low voltage
pea seed production, organic, for sowing | pea seed, organic for sowing | APOS, U - CA	Canadian-specific location; Provincial-specific provider for electricity, low voltage

pea seed production, organic, for sowing | pea seed, organic for sowing | APOS, U - CA, AB	Provincial-specific location; Provincial-specific provider for electricity, low voltage
pea seed production, organic, for sowing | pea seed, organic for sowing | APOS, U - CA, MB	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
potassium chloride production | potassium chloride | APOS, U - CA	Canadian-specific location; Provincial-specific provider for electricity, low voltage; Provincial-specific provider for electricity, medium voltage
potassium sulfate production | potassium sulfate | APOS, U - CA, AB	Provincial-specific location; Provincial-specific provider for electricity, medium voltage; Canadian-specific provider for heat, district or industrial, other than natural gas
protein pea production, organic | protein pea, organic | APOS, U - CA	Canada-specific location; Canadian-specific provider for protein pea; Canadian-specific provider for combine harvesting; removed irrigation; Canadian-specific provider for pea seed, organic, for sowing; Canadian-specific provider for solid manure loading and spreading, by hydraulic loader and spreader; Canadian-specific provider for sowing; Rest-of-World provider for tillage, currying, by weeder; Rest-of-World provider for tillage, harrowing, by spring tine harrow; Canadian-specific provider for tillage, ploughing; Rest-of-World provider for transport, tractor and trailer, agricultural
rye seed production, organic, for sowing | rye see, organic, for sowing | APOS, U - CA	Canadian-specific location; Provincial-specific provider for electricity, low voltage
rye seed production, organic, for sowing | rye see,	Provincial-specific location; Provincial-specific provider for electricity, low voltage

organic, for sowing | APOS, U - CA, AB	
rye seed production, organic, for sowing | rye see, organic, for sowing | APOS, U - CA, MB	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
soybean seed production, organic, for sowing | soybean seed, organic, for sowing | APOS, U - CA	Canada-specific location; provincial-specific location for electricity, low voltage; Canadian-specific provider for soybean, organic
soybean production, organic | soybean, organic | APOS, U - CA	Canada-specific location; Canadian-specific provider for combine harvesting; Rest-of-World provider for hoeing; removed irrigation; Canadian-specific provider for liquid manure spreading, by vacuum tanker; Canadian-specific provider for solid manure loader and spreading, by hydraulic loader and spreader, Canadian-specific provider for sowing; Rest-of-World provider for tillage, currying, by weeder; Rest-of-World provider for tillage, harrowing, by spring tine harrow; Canadian-specific provider for tillage, ploughing;
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 biowaste, home composting in heaps | compost | APOS, U - CA, AB	Provincial-specific location
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	Canadian-specific location; Provincial-specific provider for electricity, low voltage
urea production | urea | APOS, U - CA, AB	Provincial-specific location; Provincial-specific provider for electricity, low voltage
urea production | urea | APOS, U - CA, MB	Provincial-specific location; Provincial-specific provider for electricity, low voltage
wheat production, organic | wheat grain, organic | APOS, U - CA	Canadian-specific location; Canadian-specific provider for bale loading, Canadian-specific provider for bailing; Canadian-specific provider for combine harvesting; removed irrigation; Canadian-specific provider for liquid manure spreading, by vacuum tanker; Canadian-specific provider for solid manure loading and spreading, by hydraulic loader and spreader; Canadian-specific provider for sowing; Canadian-specific provider for tillage, chiselling; Rest-of-World provider for tillage, currying; Rest-of-World provider for tillage, harrowing; Canadian-specific provider for tillage, ploughing; Canadian-specific provider for wheat seed, organic, for sowing
wheat seed production, organic, for sowing | wheat seed, organic, for sowing| APOS, U - CA	Canadian-specific location; Provincial-specific provider for electricity, low voltage
wheat seed production, organic, for sowing | wheat seed, organic, for sowing| APOS, U - CA, AB	Provincial-specific location; Provincial-specific provider for electricity, low voltage
wheat seed production, organic, for sowing | wheat seed, organic, for sowing| APOS, U - CA, MB	Provincial-specific location; Provincial-specific provider for electricity, low voltage

APPENDIX G

Table G-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 (MB)	Distance to Farm Use (SK)
calcium carbonite, precipitated	Calgary, AB	Lafarge (2022)	-	721 km
Fishmeal, 63-65% protein, from fish residues	Regina, SK	Scoular (2022)	-	263 km
Phosphate rock beneficiation	Chicoutimi, QC	Arianne (2022)	2,504 km	3,415 km

APPENDIX G REFERENCES

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APPENDIX H

Table H-1. Background processes and inputs to openLCA for the production component of modelling

Process Modelled	Provider
Carbon dioxide - emissions to air/low population density[1]	Elementary flow
Occupation, annual crop, organic	Elementary Flow
Seed Inputs	Table J-1
Field Operations	Table I-1
Nutrient Application	Table K-1

[1]Input is ΔSOC from Holos modelling

APPENDIX I

Table I-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 – Canada without QC

APPENDIX J

Table J-1. Background processes and inputs to openLCA for the seed inputs component of modelling

Process Modelled	Provider
Barley seed, organic, for sowing	Barley seed production, organic, for sowing | barley seed, organic, for sowing | APOS, S – ROW
Fava bean seed, organic, for sowing	Fava bean seed production, organic, for sowing | fava bean seed, organic, for sowing | APOS, S – ROW
Grass seed, organic, for sowing	Grass seed production, organic, for sowing | grass seed, organic, for sowing | APOS, S – ROW
Lentil seed, for sowing[1]	Lentil seed production, for sowing | lentil seed, for sowing | APOS, S – GLO
Maize seed, organic, for sowing	Maize seed production, organic, for sowing | maize seed, organic, for sowing | APOS, S – ROW
Oat seed, for sowing[2]	Oat seed production, for sowing | oat seed, for sowing | APOS, U – ROW
Pea seed, organic, for sowing	Pea seed production, organic, for sowing | pea seed, organic, for sowing | APOS, S – ROW
Potato seed, organic, for setting	Potato seed production, organic, for setting | potato seed, organic, for setting, APOS, S – ROW
Rape seed, organic, for sowing	Rape seed production, organic, for sowing | rape seed, organic, for sowing | APOS, S – ROW
Rye seed, organic, for sowing	Rye seed production, organic, for sowing | rye seed, organic, for sowing | APOS, U – ROW

Soybean seed, organic, for sowing	Soybean seed production, organic, for sowing | soybean seed, organic, for sowing | APOS, S – ROW
Wheat seed, organic, for sowing[3]	Wheat seed production, organic, for sowing | wheat seed, organic, for sowing | APOS, U – ROW

[1]Proxy for organic lentil seeds

[2]Proxy for organic oat seeds

[3]Proxy for organic buckwheat seed (in addition to use for organic wheat seed)

APPENDIX K

Table K-1. Background processes and inputs to openLCA for the nutrient application component of modelling

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 L

Table L-1. Background processes and inputs to openLCA for the N fraction manure component of modelling

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 L-2. Background processes and inputs to openLCA for the P fraction manure component of modelling

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

Table L-3. Background processes and inputs to openLCA for the K fraction manure component of modelling

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

APPENDIX M

Table M-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 M-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 M-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 M-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 N

Table N-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 N-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 O

Table O-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 P

Table P-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 P REFERENCES

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APPENDIX Q

Table Q-1. Field crops and green manures with their associated dry matter (fresh) (% as fed), dry matter at harvest (% at harvest), and dry matter of grain (% as fed)

Crop	**Dry Matter (Fresh)** % as fed	**Reference**	**Dry Matter at Harvest** % at harvest	**Reference**	**Dry Matter (Grain)** % as fed	**Reference**
Rye	.25	Feedipedia (2022)	0.22 - 0.24	Darby et al. (2017)	.866	Feedipedia (2022)
Wheat	.295	Feedipedia (2022)	0.33 - 0.50	Agricultue Victoria (2022)	.87	Feedipedia (2022)
Soy	.24	Feedipedia (2022)	0.8-0.86	BASF (2019)	.87	CCOF (2015); Feedipedia (2022)
Corn	233	Feedipedia (2022)	0.2 - 0.3	Shinners et al. (2022)	863	Feedipedia (2022)
Oats	.263	Feedipedia (2022)	0.33 to 0.5	Agricultue Victoria (2022)	.879	Feedipedia (2022)
Peas	.156	Feedipedia (2022)	up to 0.2	Pulse Agronomy Network (2005)	.89	CCOF (2015)
Barley	-	-	-	-	.866	Feedipedia (2022)

Alfalfa	.199	Feedipedia (2022)	-	-	.902	Feedipedia (2022)
Lentils	-	-	-	-	.833	Feedipedia (2022)
Red Clover	.19	Feedipedia (2022)	-	-	.88	CCOF (2015); Feedipedia (2022)
Hay	-	-	-	-	0.898	CCOF (2015)
Spelt	-	-	-	-	.88	CCOF (2015)

APPENDIX Q REFERNCES

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APPENDIX R

Table Q-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 Q-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-N = [(51.81 kg N y^{-1} × 0.017 kg N_2O-N kg^{-1} N applied) + (4.40 kg N y^{-1} × 0.017 kg N_2O-N kg^{-1} N applied) + (25.88 kg N y^{-1} × 0.017 kg N_2O-N kg^{-1} N applied)]

Total N_2O-N = 1.31 kg N_2O-N

Total direct N_2O = 1.31 kg N_2O-N yr^{-1} × (44 ÷ 28 kg N_2O kg^{-1} N_2O-N)

Total direct N_2O = 2.045 kg N_2O yr^{-1} 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:

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:

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

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 Q-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)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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:

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

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:

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

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:

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 Q-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	0.87	62.51	6.6	10	Thiagarajan et al. (2018)

$F_{NitrogenL}$ = [(0.5 ÷ 0.33) × (6.6 g N kg^{-1} ÷ 1000) × 2223.945 kg ha^{-1} × 0.87] + [(0.18 ÷ 0.33) × (10 g N kg^{-1} ÷ 1000) × 2223.945 kg ha^{-1} × 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:

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

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})
- 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:

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

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. Dry matter ranges at harvest confirmed through sources in Appendix P)
- $AGR_{\%\ of\ DM}$ = 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}) (Thiafarajian et al., 2018, Table 2)

ON_1a: Rye

Table Q-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,	Feedipedia (2022)

							75% moisture)	

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

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

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 Q-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:

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

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})
- $Frac_{gasm}$ = 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}]]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 kg P ha^{-1} ÷ 3.71 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.

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

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 $[(1+0.2/80\ P_{min}) + (0.7/80\ P_{sl}) + (0.4/80\ P_{man})]$ 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 S

Table R-1. Nitrogen (N), phosphorous (P), and potassium (K) values (%) of various manure sources and their references.

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

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APPENDIX T

Table H-1. Nitrogen (N), phosphorous (P), and potassium (K) values (%) of various nutrient applications 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

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APPENDIX U

Climate Change (long term)

Arithmetic Average - Categorized

Table U-1. Climate change (long term) results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Soil Organic Carbon	Leguminous SOC	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	-981.01	-2.04	494.30	302.79	66.23	-119.73	kg CO_2 eq (long)
Oats	-401.51	0.00	247.29	284.59	44.49	147.86	kg CO_2 eq (long)
Rye	-287.20	0.00	339.96	181.15	14.41	248.32	kg CO_2 eq (long)

Weighted Average - Categorized

Table 12. Climate change (long term) results presented on a production weighted average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	**Soil Organic Carbon**	**Leguminous SOC**	**Nutrient Application**	**Field Operations**	**Seed**	**Total**	**Units**
Wheat	-178.19	-1.35	113.37	114.94	30.86	79.64	kg CO_2 eq (long)
Oats	-132.93	0.00	131.62	102.45	33.14	134.29	kg CO_2 eq (long)
Rye	-266.25	0.00	300.72	69.56	12.35	116.38	kg CO_2 eq (long)

Arithmetic Average - Uncategorized

Table U-3. Climate change (long term) results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	SOC	Legumino-us SOC	Nitrous Oxide	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	-981.01	-2.04	71.33	42.61	190.38	119.40	7.30	63.28	66.23	107.27	35.00	26.95	0.00	24.01	72.75	12.68	15.04	9.10	0.00	-119.73	kg CO_2 eq (long)
Oats	-401.51	0.00	70.06	27.69	149.54	0.00	0.00	0.00	44.49	57.98	19.07	10.66	73.47	10.98	43.98	8.56	5.17	0.00	55.39	174.86	kg CO_2 eq (long)
Rye	-287.20	0.00	136.81	0.00	203.05	0.00	0.00	0.00	14.41	33.45	11.63	14.05	98.51	0.00	6.85	10.07	00.00	6.59	0.00	248.32	kg CO_2 eq (long)

Weighted Average - Uncategorized

Table U-4. Climate change (long term) results presented on a production weighted average basis showing the breakdown of all contributions uncategorized.

Crop	SOC	Legumino-us SOC	Nitrous Oxide	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	-178.19	-1.35	43.07	3.84	16.95	2.71	5.02	41.79	30.86	40.52	16.91	28.92	0.00	0.81	6.39	7.77	7.55	6.09	0.00	79.64	kg CO_2 eq (long)
Oats	-132.93	0.00	69.04	2.65	59.93	0.00	0.00	0.00	33.14	37.92	10.93	8.05	7.03	1.05	32.90	1.82	2.46	0.00	0.29	134.29	kg CO_2 eq (long)
Rye	-266.25	0.00	143.08	0.00	157.61	0.00	0.02	0.00	12.35	29.88	10.39	1.94	22.54	0.00	0.94	1.70	0.00	2.17	0.00	116.38	kg CO_2 eq (long)

Fossil and Nuclear Energy Use

Arithmetic Average - Categorized

Table 13. Fossil and Nuclear Energy Use results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	5872.78	7059.88	414.52	10347.19	MJ deprived
Oats	2480.51	2957.12	287.11	5724.75	MJ deprived
Rye	2337.22	2535.73	107.95	4980.94	MJ deprived

Weighted Average - Categorized

Table U-6. Fossil and Nuclear Energy Use results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	953.62	1579.70	202.47	2717.79	MJ deprived
Oats	797.97	1348.21	224.11	2370.30	MJ deprived
Rye	1787.17	981.04	92.45	2860.67	MJ deprived

Arithmetic Average - Uncategorized

Table U-7. Fossil and Nuclear Energy Use results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	663.86	2686.59	1598.78	107.49	816.04	414.52	1521.85	499.86	322.91	0.00	334.09	936.16	179.62	144.61	121.33	0.00	10374.19	MJ deprived
Oats	432.28	2048.23	0.00	0.00	0.00	287.11	776.97	257.68	161.56	0.00	152.76	610.80	121.87	70.14	0.00	805.30	5724.75	MJ deprived
Rye	0.00	2337.22	0.00	0.00	0.00	107.95	474.55	166.01	178.51	1388.21	0.00	97.21	143.39	0.00	87.84	0.00	4980.94	MJ deprived

Weighted Average - Uncategorized

Table 14. Fossil and Nuclear Energy Use results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing(spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	59.84	220.78	36.28	79.88	538.82	202.47	574.84	241.41	379.17	0.00	11.20	97.57	98.48	95.48	81.17	0.00	2717.78	MJ deprived

Oats	41.36	756.61	0.00	0.00	0.00	224.11	537.96	156.00	109.28	0.00	14.61	466.91	25.89	33.30	0.00	4.23	2370.30	MJ deprived
Rye	0.00	1787.17	0.00	0.00	0.00	92.45	423.94	148.31	24.59	317.57	0.00	13.39	24.26	0.00	28.96	0.00	2860.67	MJ deprived

Freshwater Acidification

Arithmetic Average - Categorized

Table 15. Freshwater Acidification results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	**Nitrate**	**Ammonia**	**Nitrogen Oxides**	**Nutrient Application**	**Field Operations**	**Seed**	**Total**	**Units**
Wheat	3.93E-11	6.69E-12	2.10E-11	2.10E-11	1.33E-11	7.34E-12	1.23E-10	kg SO_2 eq
Oats	3.88E-11	2.66E-11	6.00E-12	7..95E-12	1.25E-11	1.34E-12	9.32E-11	kg SO_2 eq
Rye	6.58E-11	7.74E-11	1.32E-11	1.04E-11	7.72E-12	1.35E-12	1.76E-10	kg SO_2 eq

Weighted Average - Categorized

Table U-10. Freshwater Acidification results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	**Nitrate**	**Ammonia**	**Nitrogen Oxides**	**Nutrient Application**	**Field Operations**	**Seed**	**Total**	**Units**
Wheat	2.45E-11	1.30E-11	2.22E-12	2.94E-12	4.90E-12	3.40E-12	5.10E-11	kg SO_2 eq
Oats	4.35E-11	2.49E-11	4.22E-12	3.00E-12	4.55E-12	1.04E-12	8.12E-12	kg SO_2 eq
Rye	6.76E-11	5.81E-11	9.90E-12	8.14E-12	3.15E-12	1.16E-12	1.48E-10	kg SO_2 eq

Arithmetic Average - Uncategorized

Table U-11. Freshwater Acidification results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Nitrate	Ammonia	Nitrogen Oxides	Manure	Green Manure	Cover Crop	Mineral Amendments	Legumin-ous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	3.93E-11	3.54E-11	6.69E-12	1.98E-12	8.31E-12	8.10E-12	1.58E-13	2.44E-12	7.34E-12	5.32E-12	1.56E-12	9.19E-13	0.00	1.03E-12	3.01E-12	4.94E-13	6.12E-13	3.56E-13	0.00	1.23E-10	kg SO_2 eq
Oats	3.88E-11	2.66E-11	6.00E-12	1.21E-12	6.74E-12	0.00	0.00	0.00	1.34E-12	2.72E-12	8.07E-13	4.33E-13	3.08E-12	4.73E-13	1.78E-12	3.34E-13	2.11E-13	0.00	2.63E-12	9.32E-11	kg SO_2 eq
Rye	6.58E-11	7.75E-11	1.32E-11	0.00	1.04E-11	0.00	6.67E-16	0.00	1.35E-12	1.66E-12	5.20E-13	4.79E-13	4.13E-12	0.00	2.84E-13	3.93E-13	0.00	2.57E-13	0.00	1.76E-10	kg SO_2 eq

Weighted Average - Uncategorized

Table U-12. Freshwater Acidification results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Nitrate	Ammonia	Nitrogen Oxides	Manure	Green Manure	Cover Crop	Mineral Amendments	Legumin-ous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	2.45E-11	1.30E-11	2.22E-12	1.71E-13	7.87E-13	2.87E-13	8.60E-14	1.61E-12	3.40E-12	2.01E-12	7.56E-13	9.86E-136	0.00	3.47E-14	2.64E-13	3.03E-13	3.07E-13	2.38E-13	0.00	5.10E-11	kg SO_2 eq
Oats	4.35E-11	2.49E-11	4.22E-12	1.16E-13	2.88E-12	0.00	0.00	0.00	1.04E-12	1.88E-12	4.89E-13	2.93E-13	2.95E-13	4.52E-14	1.36E-12	7.09E-14	1.00E-13	0.00	1.38E-14	8.12E-11	kg SO_2 eq
Rye	6.76E-11	5.81E-11	9.90E-12	0.00	8.14E-12	0.00	1.64E-16	0.00	1.16E-12	1.48E-12	4.65E-13	6.60E-14	9.45E-13	0.00	3.91E-14	6.64E-14	0.00	8.49E-14	0.00	1.48E-10	kg SO_2 eq

Freshwater Ecotoxicity

Arithmetic Average - Categorized

Table U-13. Freshwater Ecotoxicity results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	6.47E+06	5.42E+06	6.77E+05	1.26E+07	CTUe
Oats	2.52E+06	3.28E+06	4.71E+05	6.26E+06	CTUe
Rye	1.89E+06	2.53E+06	1.64E+05	4.59E+06	CTUe

Weighted Average - Categorized

Table U-14. Freshwater Ecotoxicity results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” rep

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	1.18E+06	2.38E+06	3.32E+05	3.89E+06	CTUe
Oats	6.94E+05	1.80E+06	3.68E+05	2.86E+06	CTUe
Rye	1.46E+06	1.19E+06	1.14E+05	2.79E+06	CTUe

Arithmetic Average - Uncategorized

Table U-15. Freshwater Ecotoxicity results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	1.73E+06	2.00E+06	1.45E+06	7.71E+04	1.12E+06	6.77E+05	2.69E+06	4.05E+05	5.67E+05	0.00	3.07E+05	7.58E+05	3.61E+05	1.76E+05	1.51E+05	0.00	1.26E+07	CTUe
Oats	9.98E+05	1.52E+06	0.00	0.00	0.00	4.71E+05	1.38E+06	2.09E+05	2.80E+05	0.00	1.40E+05	4.85E+05	2.45E+05	8.54E+04	0.00	4.59E+05	6.26E+06	CTUe
Rye	0.00	1.89E+06	0.00	0.00	0.00	1.64E+05	8.4E+05	1.34E+05	3.10E+05	7.73E+05	0.00	7.72E+04	2.88E+05	0.00	1.09E+05	0.00	4.59E+06	CTUe

Weighted Average - Uncategorized

Table U-16. Freshwater Ecotoxicity results presented on a production weighted output basis showing the breakdown of all contributions uncategorized

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units

Wheat	1.47E+05	1.76E+05	3.29E+04	2.69E+04	8.01E+05	3.23E+05	1.02E+06	1.96E+05	6.62E+05	0.00	1.03E+04	8.05E+04	1.98E+05	1.16E+05	1.01E+05	0.00	8.01E+05	CTUe
Oats	9.55E+04	5.98E+05	0.00	0.00	0.00	3.68E+05	9.52E+05	1.26E+05	1.90E+05	5.51E+04	1.34E+04	3.71E+04	5.20E+04	4.05E+04	0.00	2.41E+03	2.86E+06	CTUe
Rye	0.00	1.46E+06	0.00	0.00	0.00	1.41E+05	7.50E+05	1.20E+05	4.27E+05	1.77E+07	0.00	1.06E+04	4.87E+04	0.00	3.60E+04	0.00	2.79E+06	CTUe

Freshwater Eutrophication

Arithmetic Average - Categorized

Table U-17. Freshwater Eutrophication results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Phosphate	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	0.0184	0.0095	0.0023	0.0052	0.0354	kg PO_4 P-lim eq
Oats	0.0278	0.0046	0.0026	0.0016	0.0366	kg PO_4 P-lim eq
Rye	0.0062	0.0059	0.0016	0.0012	0.0149	kg PO_4 P-lim eq

Weighted Average - Categorized

Table U-18. Freshwater Eutrophication results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Phosphate	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	0.0120	0.0015	0.0008	0.0024	0.0168	kg PO_4 P-lim eq
Oats	0.0156	0.0015	0.0009	0.0012	0.0228	kg PO_4 P-lim eq
Rye	0.0055	0.0047	0.0006	0.0011	0.0119	kg PO_4 P-lim eq

Arithmetic Average - Uncategorized

Table U-19. Freshwater Eutrophication results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Phosphate	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	0.0184	0.0017	0.0035	0.0029	0.0002	0.0011	0.0052	0.0008	0.0003	0.0001	0.00	0.0001	0.0006	8.04E-5	7.9E-5	6.25E-5	0.00	0.0354	kg PO_4 P-lim eq
Oats	0.0248	0.0014	0.0032	0.00	0.00	0.00	0.0016	0.0004	0.0001	5.9E-5	0.0007	9.36E-5	0.0004	5.7E-5	3.83E-5	0.00	0.0005	0.0366	kg PO_4 P-lim eq
Rye	0.0062	0.00	0.0059	0.00	0.00	0.00	0.0012	0.0002	0.0001	6.44E-5	0.0009	0.00	6.36E-5	6.42E-5	0.00	4.53E-5	0.00	0.0149	kg PO_4 P-lim eq

Weighted Average - Uncategorized

Table U-20. Freshwater Eutrophication results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Phosphate	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units

Wheat	0.0120	0.0002	0.0004	6.76E-5	0.0002	0.0007	0.0025	0.0003	0.0002	0.0001	0.00	6.84E-6	5.96E-5	4.42E-5	5.12E-5	4.17E-5	0.00	0.0168	kg PO_4 P-lim eq
Oats	0.0189	0.0001	0.0017	0.00	0.0000	0.0000	0.0012	0.0003	0.0001	3.95E-5	6.98E-5	8.96E-6	0.0003	1.13E-5	1.52E-5	0.00	3.05E-6	0.0228	kg PO_4 P-lim eq
Rye	0.0055	0.0000	0.0047	0.00	0.0000	0.0000	0.0011	0.0003	0.0001	8.88E-6	0.0002	0.00	8.76E-6	1.08E-5	0.00	1.5E-5	0.00	0.0119	kg PO_4 P-lim eq

Ionizing Radiation

Arithmetic Average - Categorized

Table U-21. Ionizing Radiation results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	2599.69	1914.51	181.13	4695.33	Bq C-14 eq
Oats	1100.37	1367.14	108.10	2575.61	Bq C-14 eq
Rye	1058.30	1177.23	48.56	2284.09	Bq C-14 eq

Weighted Average - Categorized

Table U-22. Ionizing Radiation results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	446.37	762.45	95.22	1304.03	Bq C-14 eq
Oats	376.50	676.64	84.38	1137.53	Bq C-14 eq
Rye	810.95	456.16	41.69	1308.81	Bq C-14 eq

Arithmetic Average - Uncategorized

Table U-23. Ionizing Radiation results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	172.72	1305.81	657.17	62.13	401.87	181.13	720.06	226.81	166.45	0.00	155.10	426.71	91.21	69.41	58.76	0.00	4695.33	Bq C-14 eq
Oats	101.48	998.89	0.00	0.00	0.00	108.10	367.63	116.99	83.46	0.00	70.92	277.86	61.89	33.67	0.00	354.73	2575.61	Bq C-14 eq
Rye	0.00	1058.30	0.00	0.00	0.00	48.56	224.53	75.37	92.21	625.52	0.00	44.23	72.81	0.00	42.54	0.00	2284.09	Bq C-14 eq

Weighted Average - Uncategorized

Table U-24. Ionizing Radiation results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	14.85	104.36	14.92	46.90	265.35	95.22	271.98	109.60	195.77	0.00	5.20	44.57	50.18	45.83	39.31	0.00	1304.03	Bq C-14 eq

Oats	9.71	366.80	0.00	0.00	0.00	84.38	254.54	70.82	56.45	44.63	6.79	212.40	13.15	15.99	0.00	1.86	1137.53	Bq C-14 eq
Rye	0.00	810.95	0.00	0.00	0.00	41.69	200.59	67.34	12.70	143.10	0.00	6.09	12.32	0.00	14.03	0.00	1308.81	Bq C-14 eq

Land Occupation, Biodiversity

Arithmetic Average - Categorized

Table U-25. Land Occupation, Biodiversity results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	6.48	4.07	0.34	10.90	m^2 arable land eq yr
Oats	2.86	3.37	0.29	6.52	m^2 arable land eq yr
Rye	1.85	1.92	0.11	3.88	m^2 arable land eq yr

Weighted Average - Categorized

Table U-26. Land Occupation, Biodiversity results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	1.35	1.80	0.21	3.35	m^2 arable land eq yr
Oats	0.75	1.33	0.22	2.31	m^2 arable land eq yr
Rye	1.43	0.79	0.10	2.31	m^2 arable land eq yr

Arithmetic Average - Uncategorized

Table U-27. Land Occupation, Biodiversity results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	1.61	2.07	1.37	0.24	1.19	0.34	1.19	0.52	0.45	0.00	0.49	0.75	0.21	0.28	0.19	0.00	10.90	m^2 arable land eq yr
Oats	1.18	1.67	0.00	0.00	0.00	0.29	0.63	0.28	0.25	0.52	0.22	0.50	0.14	0.14	0.00	0.69	6.52	m^2 arable land eq yr
Rye	0.00	1.85	0.00	0.00	0.00	0.11	0.39	0.18	0.27	0.70	0.00	0.08	0.16	0.00	0.13	0.00	3.88	m^2 arable land eq yr

Weighted Average - Uncategorized

Table U-28. Land Occupation, Biodiversity results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	0.16	0.17	0.03	0.21	0.78	0.21	0.45	0.25	0.57	0.00	0.02	0.08	0.11	0.19	0.12	0.00	3.35	m^2 arable land eq yr

Oats	0.11	0.64	0.00	0.00	0.00	0.22	0.44	0.17	0.17	0.05	0.02	0.38	0.03	0.07	0.00	0.00	2.31	m^2 arable land eq yr
Rye	0.00	1.43	0.00	0.00	0.00	0.10	0.35	0.16	0.04	0.16	0.00	0.01	0.03	0.00	0.04	0.00	2.31	m^2 arable land eq yr

Mineral Resource Use

Arithmetic Average - Categorized

Table U-29. Mineral Resource Use results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	3.77	2.04	0.63	6.44	kg deprived
Oats	1.62	1.55	0.44	3.61	kg deprived
Rye	1.15	0.89	0.16	2.21	kg deprived

Weighted Average - Categorized

Table U-30. Mineral Resource Use results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	0.57	0.91	0.30	1.77	kg deprived
Oats	0.51	0.65	0.34	1.51	kg deprived
Rye	0.90	0.38	0.14	1.41	kg deprived

Arithmetic Average - Uncategorized

Table U-31. Mineral Resource Use results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	0.80	1.54	0.82	0.10	0.52	0.63	0.67	0.23	0.25	0.00	0.20	0.38	0.11	0.11	0.08	0.00	6.44	kg deprived
Oats	0.43	1.19	0.00	0.00	0.00	0.44	0.34	0.12	0.13	0.21	0.09	0.24	0.08	0.06	0.00	0.29	3.61	kg deprived
Rye	0.00	1.15	0.00	0.00	0.00	0.16	0.21	0.08	0.14	0.28	0.00	0.04	0.09	0.00	0.06	0.00	2.21	kg deprived

Weighted Average - Uncategorized

Table U-32. Mineral Resource Use results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	0.07	0.12	0.02	0.02	0.34	0.30	0.25	0.11	0.30	0.00	0.01	0.04	0.06	0.08	0.06	0.00	1. 77	kg deprived

Oats	0.04	0.47	0.00	0.00	0.00	0.34	0.24	0.07	0.09	0.02	0.01	0.18	0.02	0.03	0.00	0.00	1. 51	kg deprived
Rye	0.00	0.90	0.00	0.00	0.00	0.14	0.19	0.07	0.02	0.06	0.00	0.01	0.02	0.00	0.02	0.00	1.41	kg deprived

Ozone Layer Depletion

Arithmetic Average - Categorized

Table U-33. Ozone Layer Depletion results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	7.08E-05	4.77E-05	4.81E-06	1.23E-04	kg CFC-11 eq
Oats	3.03E-05	5.16E-05	2.67E-06	8.47E-05	kg CFC-11 eq
Rye	3.03E-05	3.22E-05	1.15E-06	6.36E-05	kg CFC-11 eq

Weighted Average - Categorized

Table U-34. Ozone Layer Depletion results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	1.05E-05	1.70E-05	2.25E-06	2.98E-05	kg CFC-11 eq
Oats	1.02E-05	1.76E-05	2.28E-06	3.01E-05	kg CFC-11 eq
Rye	2.31E-05	1.23E-05	9.84E-07	3.64E-05	kg CFC-11 eq

Arithmetic Average - Uncategorized

Table U-35. Ozone Layer Depletion results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	4.53E-06	3.66E-05	1.97E-05	1.53E-06	8.43E-06	4.81E-06	1.81E-05	6.59E-06	2.41E-06	0.00E+00	4.07E-06	1.21E-05	1.60E-06	1.57E-06	1.25E-06	0.00E+00	1.23E-04	kg CFC-11 eq
Oats	2.87E-06	2.75E-05	0.00E+00	0.00E+00	0.00E+00	2.67E-06	9.23E-06	3.40E-06	1.19E-06	1.46E-05	1.86E-06	7.96E-06	1.09E-06	7.60E-07	0.00E+00	1.16E-05	8.47E-05	kg CFC-11 eq
Rye	0.00E+00	3.03E-05	0.00E+00	0.00E+00	0.00E+00	1.15E-06	5.64E-06	2.19E-06	1.31E-06	1.96E-05	0.00E+00	1.27E-06	1.28E-06	0.00E+00	9.07E-07	0.00E+00	6.36E-05	kg CFC-11 eq

Weighted Average - Uncategorized

Table U-36. Ozone Layer Depletion results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	4.03E-07	2.96E-06	4.46E-07	1.17E-06	5.57E-06	2.25E-06	6.83E-06	3.18E-06	2.80E-06	0.00E+00	1.36E-07	1.26E-06	8.82E-07	1.03E-06	8.38E-07	0.00E+00	2.98E-05	kg CFC-11 eq

Oats	2.74E-07	9.95E-06	0.00E+00	0.00E+00	0.00E+00	2.28E-06	6.39E-06	2.06E-06	8.03E-07	1.40E-06	1.78E-07	6.09E-06	2.31E-07	3.61E-07	0.00E+00	6.08E-08	3.01E-05	kg CFC-11 eq
Rye	0.00E+00	2.31E-05	0.00E+00	0.00E+00	0.00E+00	9.84E-07	5.04E-06	1.96E-06	1.81E-07	4.47E-06	0.00E+00	1.75E-07	2.16E-07	0.00E+00	2.99E-07	0.00E+00	3.64E-05	kg CFC-11 eq

Particulate Matter Formation

Arithmetic Average - Categorized

Table U-37. Particulate Matter Formation results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Ammonia	Nitrogen Oxides	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	0.69	0.02	0.24	0.16	0.13	1.25	kg PM2.5 eq
Oats	0.52	0.02	0.10	0.15	0.02	0.81	kg PM2.5 eq
Rye	1.52	0.05	0.15	0.10	0.02	1.84	kg PM2.5 eq

Weighted Average - Categorized

Table U-38. Particulate Matter Formation results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Ammonia	Nitrogen Oxides	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	0.26	0.01	0.04	0.07	0.06	0.43	kg PM2.5 eq
Oats	0.49	0.01	0.04	0.06	0.02	0.62	kg PM2.5 eq
Rye	1.14	0.03	0.12	0.04	0.02	1.35	kg PM2.5 eq

Arithmetic Average - Uncategorized

Table U-39. Particulate Matter Formation results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Ammonia	Nitrogen Oxides	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	0.69	0.02	0.02	0.10	0.08	0.00	0.04	0.13	0.06	0.02	0.02	0.00	0.01	0.04	0.01	0.01	0.01	0.00	1.25	kg PM2.5 eq
Oats	0.52	0.02	0.01	0.09	0.00	0.00	0.00	0.02	0.03	0.01	0.01	0.04	0.01	0.02	0.01	0.00	0.00	0.03	0.81	kg PM2.5 eq
Rye	1.52	0.05	0.00	0.15	0.00	0.00	0.00	0.02	0.02	0.01	0.01	0.05	0.00	0.00	0.01	0.00	0.00	0.00	1.84	kg PM2.5 eq

Weighted Average - Uncategorized

Table U-40. Particulate Matter Formation results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Ammonia	Nitrogen Oxides	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units

Wheat	0.26	0.01	0.00	0.01	0.00	0.00	0.02	0.06	0.02	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	kg PM2.5 eq
Oats	0.49	0.01	0.00	0.04	0.00	0.00	0.00	0.02	0.02	0.01	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.62	kg PM2.5 eq
Rye	1.14	0.03	0.00	0.12	0.00	0.00	0.00	0.02	0.02	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	1.35	kg PM2.5 eq

Photochemical Oxidant Formation

Arithmetic Average - Categorized

Table U-41. Photochemical Oxidant Formation results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nitrogen Oxides	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	2.14	3.70	2.96	0.30	9.10	kg NMVOC eq
Oats	1.45	1.16	3.17	0.12	5.89	kg NMVOC eq
Rye	4.21	1.75	1.95	0.08	8.00	kg NMVOC eq

Weighted Average - Categorized

Table U-42. Photochemical Oxidant Formation results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. "SOC flux" represents the field-level carbon dioxide emissions associated with production.

Crop	Nitrogen Oxides	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	0.71	0.56	1.14	0.15	2.56	kg NMVOC eq
Oats	1.35	0.38	1.11	0.09	2.94	kg NMVOC eq
Rye	3.16	1.34	0.79	0.07	5.36	kg NMVOC eq

Arithmetic Average - Uncategorized

Table U-43. Photochemical Oxidant Formation results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Nitrogen Oxides	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	2.14	0.13	1.96	1.06	0.53	0.53	0.30	1.27	0.40	0.19	0.00	0.14	0.68	0.10	0.10	0.08	0.00	9.10	kg NMVOC eq
Oats	1.45	0.08	1.08	0.00	0.00	0.00	0.12	0.65	0.21	0.09	0.83	0.12	0.44	0.07	0.05	0.00	0.71	5.89	kg NMVOC eq
Rye	4.21	0.00	1.75	0.00	0.00	0.00	0.08	0.40	0.13	0.10	1.11	0.00	0.07	0.08	0.00	0.06	0.00	8.00	kg NMVOC eq

Weighted Average - Uncategorized

Table U-44. Photochemical Oxidant Formation results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Nitrogen Oxides	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units

Wheat	0.71	0.01	0.16	0.02	0.01	0.35	0.15	0.48	0.19	0.20	0.00	0.01	0.07	0.06	0.07	0.06	0.00	2.56	kg NMVOC eq
Oats	1.35	0.01	0.38	0.00	0.00	0.00	0.09	0.45	0.13	0.06	0.08	0.01	0.34	0.01	0.02	0.00	0.00	2.94	kg NMVOC eq
Rye	3.16	0.00	1.34	0.00	0.00	0.00	0.07	0.36	0.12	0.01	0.25	0.00	0.01	0.01	0.00	0.02	0.00	5.36	kg NMVOC eq

Terrestrial Acidification

Arithmetic Average - Categorized

Table U-45. Terrestrial Acidification results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Ammonia	Nitrate	Nitrogen Oxides	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	5.18E-05	2.70E-05	4.59E-06	7.62E-06	8.41E-06	9.61E-06	1.11E-04	kg SO_2 eq
Oats	3.86E-05	2.62E-05	4.12E-06	7.12E-06	8.21E-06	1.37E-06	8.56E-05	kg SO_2 eq
Rye	1.13E-04	4.52E-05	8.95E-06	9.78E-06	5.08E-06	1.69E-06	1.84E-04	kg SO_2 eq

Weighted Average - Categorized

Table U-46. Terrestrial Acidification results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Ammonia	Nitrate	Nitrogen Oxides	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	1.90E-05	1.68E-05	1.52E-06	7.92E-07	3.20E-06	4.42E-06	4.69E-05	kg SO_2 eq
Oats	3.63E-05	2.97E-05	2.90E-06	2.57E-06	2.98E-06	1.07E-06	7.56E-05	kg SO_2 eq
Rye	8.46E-05	4.65E-05	6.70E-06	7.67E-06	2.07E-06	1.45E-06	1.49E-04	kg SO_2 eq

Arithmetic Average - Uncategorized

Table U-47. Terrestrial Acidification results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Ammonia	Nitrate	Nitrogen Oxides	Manure	Green Manure	Cover Crop	Mineral Amendments	Legumin-ous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	5.18E-05	2.70E-05	4.59E-06	1.26E-06	5.75E-06	5.02E-07	1.01E-07	1.65E-06	9.61E-06	3.49E-06	1.03E-06	5.54E-07	0.00E+00	6.80E-07	1.82E-06	3.15E-07	2.83E-07	2.31E-07	0.00E+00	1.11E-04	kg SO_2 eq
Oats	3.86E-05	2.62E-05	4.12E-06	1.62E-06	5.49E-06	0.00E+00	0.00E+00	0.00E+00	1.37E-06	1.78E-06	5.36E-07	2.77E-07	2.05E-06	3.11E-07	1.17E-06	2.10E-07	1.37E-07	0.00E+00	1.74E-06	8.56E-05	kg SO_2 eq
Rye	1.13E-04	4.52E-05	8.95E-06	0.00E+00	9.77E-06	0.00E+00	9.78E-10	0.00E+00	1.69E-06	1.09E-06	3.43E-07	3.06E-07	2.74E-06	0.00E+00	1.87E-07	2.47E-07	0.00E+00	1.67E-07	0.00E+00	1.84E-04	kg SO_2 eq

Weighted Average - Uncategorized

Table U-48. Terrestrial Acidification results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Ammonia	Nitrate	Nitrogen Oxides	Manure	Green Manure	Cover Crop	Mineral Amendments	Legumin-ous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	1.90E-05	1.68E-05	1.52E-06	1.10E-07	6.17E-07	1.14E-08	5.46E-08	1.09E-06	4.42E-06	1.32E-06	4.99E-07	6.50E-07	0.00E+00	2.28E-08	1.95E-07	1.74E-07	1.87E-07	1.55E-07	0.00E+00	4.69E-05	kg SO_2 eq
Oats	3.63E-05	2.97E-05	2.90E-06	1.01E-06	1.56E-06	0.00E+00	0.00E+00	0.00E+00	1.07E-06	1.23E-06	3.23E-07	1.87E-07	1.96E-07	2.98E-08	8.96E-07	4.43E-08	6.52E-08	0.00E+00	9.17E-09	7.56E-05	kg SO_2 eq
Rye	8.46E-05	4.65E-05	6.70E-06	0.00E+00	7.67E-06	0.00E+00	2.41E-10	0.00E+00	1.45E-06	9.72E-07	3.07E-07	4.21E-08	6.28E-07	0.00E+00	2.57E-08	4.21E-08	0.00E+00	5.52E-08	0.00E+00	1.49E-04	kg SO_2 eq

Water Scarcity

Arithmetic Average - Categorized

Table U-49. Water Scarcity results presented on an arithmetic average basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	118.47	44.65	-531.76	-368.64	m^3 world-eq
Oats	88.30	37.49	11.76	137.54	m^3 world-eq
Rye	138.53	27.10	9.64	175.27	m^3 world-eq

Weighted Average - Categorized

Table U-50. Water Scarcity results presented on a production weighted output basis with categories including "Nutrient Application" and Field Operations". Nutrient application includes impacts from cover crops, green manures, the proceeding leguminous crop, mineral amendments, manure, and field level emissions (nitrous oxide, nitrate, ammonia, and phosphate), unless otherwise indicated. Field operations include impacts from disking, harrowing (rotary and spring tine are distinguished), harvesting, ploughing, rolling, sowing, swathing, tilling, and weeding. “SOC flux” represents the field-level carbon dioxide emissions associated with production.

Crop	Nutrient Application	Field Operations	Seed	Total	Units
Wheat	-4.85	20.51	-28.50	-12.84	m^3 world-eq
Oats	35.50	15.16	9.18	59.84	m^3 world-eq
Rye	110.92	10.28	8.30	129.49	m^3 world-eq

Arithmetic Average - Uncategorized

Table U-51. Water Scarcity results presented on an arithmetic average basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	62.82	37.41	43.62	4.16	-29.54	-531.76	17.15	4.04	5.81	0.00	3.35	7.75	3.03	1.88	1.65	0.00	-368.64	m^3 world-eq
Oats	43.29	45.01	0.00	0.00	0.00	11.76	8.76	2.11	3.09	9.52	1.53	4.95	2.05	0.91	0.00	4.56	137.54	m^3 world-eq
Rye	0.00	138.53	0.00	0.00	0.00	9.64	5.35	1.39	3.42	12.77	0.00	0.79	2.42	0.00	0.97	0.00	175.27	m^3 world-eq

Weighted Average - Uncategorized

Table U-52. Water Scarcity results presented on a production weighted output basis showing the breakdown of all contributions uncategorized.

Crop	Manure	Green Manure	Cover Crop	Mineral Amendments	Leguminous Crop	Seed	Harvesting	Sowing	Harrowing (rotary)	Ploughing	Harrowing (spring tine)	Tillage	Disking	Weeding	Rolling	Swath	Total	Units
Wheat	5.88	6.24	0.99	1.55	-19.51	-28.50	6.48	1.95	7.13	0.00	0.11	0.82	1.67	1.24	1.10	0.00	-12.84	m^3 world-eq
Oats	4.14	31.35	0.00	0.00	0.00	9.18	6.06	1.27	2.09	0.91	0.15	3.78	0.44	0.43	0.00	0.02	59.84	m^3 world-eq
Rye	0.00	110.92	0.00	0.00	0.00	8.30	4.77	1.27	0.47	2.92	0.00	0.11	0.41	0.00	0.32	0.00	129.49	m^3 world-eq

APPENDIX V

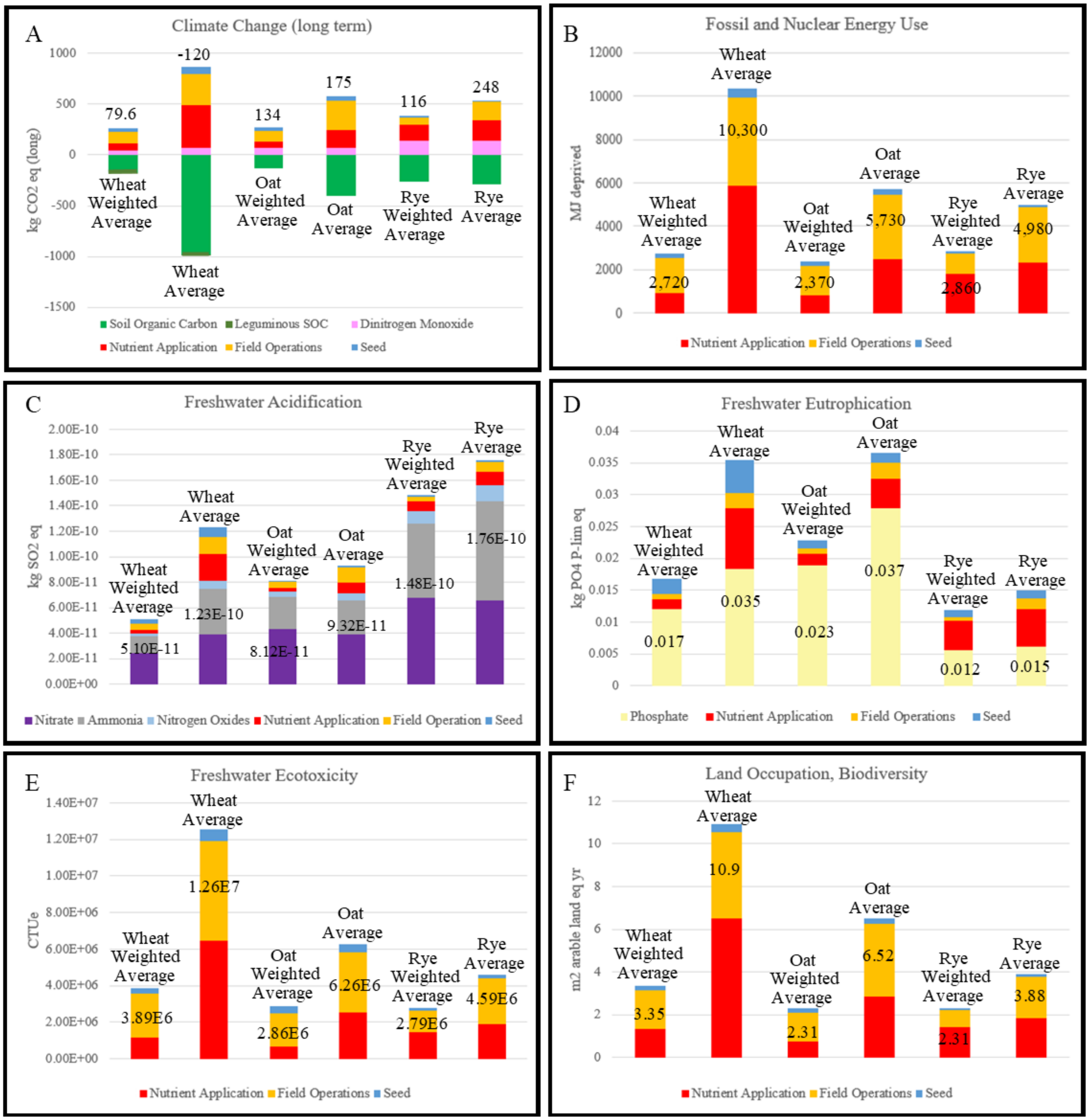

Figure V-1. Results of the six impact categories of interest in detail (categorized, unless otherwise indicated)