Canadian Organic Growers
Cultivons Biologique Canada

Appendix 2: Environmental Impacts Technical Reports

Organic Task Force Report: Cultivating the Organic Opportunity for Canadian Farmers and Consumers

2.1 Soil Health in Organic Agriculture Systems

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Context

Healthy soils are the foundation of productive systems. In agriculture, soil health is defined as the ability of the soil to produce high-quality food with minimal inputs. Soil health is the result of multiple interactions between physical, chemical, and biological soil functions (Bünemann et al., 2018). Therefore, soil health indicators need to reflect soil functions. For example, because soil organic carbon (SOC) is the key element that influences multiple soil functions, SOC and labile SOC fractions [particulate (POM-C), permanganate oxidizable (POXc), mineralizable C] are essential components and measures of soil health (Hurisso et al., 2016; Norris et al., 2020). Therefore, relative to other soil properties, more studies on SOC and SOC fractions are included in this review of soil health.

Soil health is important to organic producers. Cranfield et al. (2010) found that health and environmental concerns were a greater motivation than economic considerations for conversion to organic production in Canada. Interviews with 34 producers in Atlantic Canada found that organic producers had a more holistic definition of soil health than conventional producers (Mann et al., 2021). They also tended to be more open to more comprehensive soil health assessments that include chemical, physical, and biological soil properties, such as the Cornell Soil Health Assessment (CSHA). In a study conducted on three organic farms in southwestern Ontario, Hargreaves et al. (2019) found that organic producers' perceptions of productivity and soil health were associated with physical, biological and chemical soil properties.

This review draws on reviews and meta-analyses to compare organic and conventional agriculture in a Canadian context. It is organized as follows:

1. Comparisons of soil health under organic and conventional cropping systems.
2. Comparisons of soil health under organic and conventional horticultural systems.
3. Best management practices to improve soil health.

1. Field crops

No meta-analysis specific to soil health in organic field crops was found. However, many meta-analyses compared SOC content and concentration. These meta-analyses show that organic farms have higher soil organic carbon (SOC) concentrations and soil C stocks than conventional farms (Mondelaers et al., 2009; Gomiero et al., 2011; Gattinger et al., 2012; Tuomisto et al., 2012; García-Palacios et al., 2018). However, in a recent meta-analysis, Alvarez and Cayuela (2022) reviewed 83 head-to-head comparisons of organic and conventional systems. They found that organic systems increased SOC compared to conventional systems, but mostly because of external sources of C (manure from animal production or residue retention). They concluded that organic farming itself does not increase SOC. García-Palacios et al. (2018) found that organic systems had higher soil respiration, SOC stocks, and SOC sequestration rates than conventional systems. Their main explanation was the source of fertilization in organic systems, an external source of carbon inputs. They also hypothesize that crop traits (e.g., leaf N and fine-root C and N) also play an important role in the effects of organic systems on SOC stocks and sequestration rates.

Long-term agroecosystem research experiments around the world have compared organic field cropping systems with conventional ones. Most of these studies have collected soil health data over many years. In the majority of these studies, organic systems generally have higher SOC content or concentration than conventional systems when an external C source is used (Teasdale et al., 2007; Delate et al., 2013; Omondi et al., 2022; Mayer et al., 2022). This is reflected in other soil health indicators such as SOM, POM-C, MBC (microbial carbon biomass), POXc (Spargo et al., 2011; Wortman et al., 2011; Delate et al., 2013; Braman et al., 2016; Krauss et al., 2022; Mayer et al. 2022; Lori et al., 2023; Rodale Institute, 2021). However, in P and N deficient systems, organic systems do not outperform conventional systems (Malhi et al., 2009; Bell et al., 2012). Furthermore, soil health in organic systems tends to be similar to conventional ones when organic systems are compared to conventional systems using best management practices such as no-till, cover crops, or manure amendments (Green et al., 2005; Spargo et al., 2011).

Organically managed soils tended to have higher aggregate stability (Lotter et al., 2003; Green et al., 2005; Gomiro et al., 2011; Stainsby et al., 2022). Bulk density has also been reported to be lower in organically managed soils than in conventional soils after 40 years in the USA (Rodale Institute, 2021). Organically managed soils also tended to have higher pH, K, P and N availability (Birkhofer et al., 2008; Wortman et al., 2011; Delate et al., 2013), although in some cases P depletion has been observed in organically managed soils (Malhi et al., 2009; Welsh et al., 2009; Fraser et al., 2019).

2. Horticulture

2.1. Fruits and vegetables

Soil health literature in organic horticultural crops is especially scarce in Canada. A long-term study in Italy (Campanilli and Capi, 2012) reported that over a nine-year period, the SOC and TN content of the organic management system increased over time following the conversion period, while the SOC and TN content of the conventionally managed soils tended to remain unchanged. In California, USA, Reganold et al. (2010) measured soil health in 13 paired organic and conventional strawberry fields. They reported that organic soils had higher SOC, TN, MBC, and mineralizable C than conventional soils. In an on-farm survey conducted in Quebec, preliminary results suggest that organic commercial farms had higher topsoil SOM content and lower soil bulk density compared to conventional farms (Bélanger et al., 2024). In a study conducted on mixed commercial farms in southwestern British Columbia, Norgaard et al. (2022) found no difference in POXc and soil N-NO3 between management strategies. Residual P was eight times higher with high compost than with low compost. In their study, 80% of the farms were organic. In a study conducted on thirty organic mixed vegetable farms in Michigan, USA, Kaufman et al. (2020) reported that BMPs such as tillage depth, cover crop use, and types of soil amendments could increase SOM levels on organic farms. Looking at different management strategies in organic vegetable systems in the US, Prichett et al. (2011) reported that organic amendments had the greatest short-term effect on SOC and bulk density compared to reduced tillage and cover crops.

In Eastern Canada, two soil health assessments were conducted on commercial potato farms. Potato rotations in Eastern Canada typically include cereals and are therefore discussed separately from other vegetable studies. In New Brunswick, Nesbit et al. (2014) found that the mean abundance of nematodes, mite suborders and Collembola families did not differ significantly between organic and conventional fields. However, in the same study, organically managed fields had MBC, pH, soil moisture, litter light fraction, and lower C:N ratio and bulk density than the conventional fields. Boiteau et al. (2014) also evaluated soil health in four systems in New Brunswick. They found that conventional production systems had the lowest levels of biological parameters (i.e., earthworm abundance, biomass, soil respiration, Acari, and Collembola abundance) compared to organic potato fields, an abandoned potato field, and pasture. They also reported that conventional systems had the highest P content and P saturation, while organic systems had the highest soil TN and calcium content. In Prince Edward Island and New Brunswick, Nelson et al. (2009) evaluated soil health in extensive potato rotations (i.e., potato phases followed by 4 years of forage) and found a recovery in earthworm abundance and biomass two years after the potato phase, while other soil health parameters remained unchanged.

2.2. Vineyard

Vineyard studies comparing organic to conventional management were mostly conducted in Europe. In a long-term study of organic, biodynamic, and integrated vineyard management in Italy, Simona et al. (2024) found that the sustainability level of organic vineyards was higher than that of integrated vineyards. However, when looking specifically at soil health, bacterial species richness and diversity and SOC storage in integrated management production were similar to those in organic production systems. These results are similar to those reported by Meissner et al. (2019) and Gutiérrez-Gamboa et al. (2019) in studies conducted on research farms. Both reported similar soil health parameters in organic vineyards compared to integrated vineyards. Other studies conducted on commercial vineyards reported similar soil health between conventional and organic vineyards (Vavoulidou et al., 2006; Wheeler and Crips, 2011; Van Geel et al., 2017; Unc et al., 2021). Nevertheless, other studies conducted in commercial vineyards reported higher soil health in organically managed vineyards compared to conventional vineyards (Coll et al., 2014; Brunori et al., 2016; Orkur et al., 2016; Amaral et al., 2022). Interestingly, Coll et al. (2014) reported that most soil health parameters (e.g., SOC, available P and K, and microbial biomass) were higher than in conventional vineyards after 11 years of organic management, but not after only 7 years. However, organic vineyards appear to be detrimental to earthworms in some cases (Coll et al., 2014; Beaumelle et al., 2023). The use of copper in organic orchards may explain lower earthworm abundance (Steinmetz et al., 2017). On-farm studies assume that conventional and organic vineyards have identical soil characteristics at the time of conversion, which limits the conclusions that can be drawn from on-farm studies and emphasizes the importance of long-term studies to assess soil health (Probst et al., 2008).

2.3. Orchards

Most of the soil health data available for orchards comes from commercial farm comparisons. These on-farm studies suggest that organic orchards support soil health parameters compared to conventional orchards. For example, a study of mixed fruit orchards in Cyprus found that soils in organic orchards had higher SOM mean weight diameter and respiration than conventional mixed fruit orchards (Ioannidou et al., 2022). In Spain, Herencia et al. (2019) reported higher SOM, TN, available P, Mg, earthworm abundance and microorganisms in organic plum orchards than in conventional plum orchards. However, another study conducted in commercial orchards in Belgium showed that SOC, SOM, TN, and bulk density did not differ between integrated and organic orchards (Dealemans et al., 2022). Similar results were reported by Orpet et al. (2020) as soil health parameters did not differ between transition, organic, and conventional apple orchards in the USA. In a study conducted at a research farm in Washington, Glover et al. (2000) reported that the integrated apple orchard had a higher soil health score than the conventional orchard. The organic production system did not result in a significantly different soil health score than the other two management systems. In this study, both the integrated and organic orchards had lower bulk density and higher MBC than the conventional apple orchard.

3. Best management practices

In a systematic review, Tully and McAskill (2020) reported 17 studies where **reduced tillage** in organic systems resulted in higher topsoil SOC and microbial biomass compared to conventional tillage. Reduced tillage was also associated with greater soil stratification compared to conventional tillage in most of these studies. They also reported increased soil aggregate stability in four studies, increased water content in one study, and reduced soil erosion in three studies. However, most of the comparisons do not account for variability in tillage intensity and frequency (Tully and McAskill, 2020). In an on-farm survey in the Midwestern organic corn system, Sprunger et al. (2021) reported that tillage intensity was associated with increased crop diversity and decreased soil health. Research on organic no-till has been conducted in Canada. In a review of no-till research projects conducted in Eastern Canada, Halde et al. (2017) reported that the fact that soil health was not measured was a research gap. In a study conducted in Nova Scotia comparing different green manure termination strategies, Marshall and Lynch (2018) found that three years after green manure termination, topsoil SOC was higher in the no-tilled green manure compared to the tilled green manure. In the same experiment, they also found lower earthworm abundance in the tilled treatment compared to no-till; however, the earthworm population recovered three years after tilling (Marshall and Lynch, 2018). In Western Canada, Halde et al. (2014) investigated the adaptation of no-till practices to include cover crop mulch. They found a similar yield under the organic no-till system as the organic tilled system (Halde et al., 2014). Halde et al. (2015) compared different types of cover crop mulch and reported that hairy vetch mulch was the best option for N supply and weed control. SOC, P, and pH did not vary between treatments. No other soil health parameters were measured in these systems. Future organic no-till trials in Canada should be conducted over a longer period of time and include soil health measurements.

The use of **cover crops** in crop rotations does not always increase SOC. In a meta-analysis of different BMPs in organic systems, Crystal-Ornelas et al. (2021) found that cover crops increased SOC by 10% compared to no cover crops. They also found a temporal trend where the effects of cover crops were significant 5 years after adoption. Incorporating cover crops into the rotation may be more beneficial when combined with organic amendments.

Studies have found that the combination of cover crop use with animal manure application can improve N use efficiency (Torstensson et al., 2006), soil N availability (Chirinda et al., 2010; Kauer et al., 2015; Spargo et al., 2016), and soil respiration (Chirinda et al., 2010). The combination of cover crop use and organic amendments can reduce animal manure application rates and improve nitrogen use efficiency. The benefits of cover crops on cash crop yields have been demonstrated in eastern Canada. Lavergne et al. (2021) found that cover crops seeded after grain harvest increased soil nitrates in the following spring, contributing to corn yield. Similar results have been reported for organic wheat (Alam et al., 2018) and organic potatoes (Alam et al., 2016). The use of cover crops in organic systems does not always result in higher soil health (McNeil et al., 2023) or higher cash crop yields (Evans et al., 2016), leaving room for optimization of cover crops depending on both region and system (Thiessen Martens, 2019).

Adding **forages** to organic crop rotations can improve soil health (Sprunger et al., 2021). A meta-analysis showed that organic farms tend to have longer crop rotations, resulting in higher diversity than conventional farms (Barbieri et al., 2017). Including alfalfa in organic cereal rotations increases SOC (Wander et al., 2007; Welsh et al., 2009) and soil biological activity (Wander et al., 2007; Braman et al., 2016). Over a 5-year rotation, Wachter et al. (2019) found that SOC remained unchanged after two organic rotations with alfalfa, but decreased under conventional management. There are some exceptions (Bell et al., 2012; Wortman et al., 2011; Blanco-Canqui et al., 2017; Spargo et al., 2011). Including alfalfa in grain rotations can also increase soil nitrogen (Welsh et al., 2009; Spargo et al., 2011).

Integrating livestock into organic cropping systems could improve soil health and SOC status. Integrated livestock is a great opportunity for grazing crop residues (Rakkar and Blanco-Canqui, 2018). Livestock can be integrated in different ways in cropping systems (e.g., lambs and goats in vineyards and orchards, cattle in mixed crop farms, or chickens in vegetable farms). Long-term studies and global systematic comparisons of soil health in organic and conventional field crop systems suggest that efficient stockless organic systems rely on external sources of manure (e.g., Omondi et al., 2022; Mayer et al., 2022). Smith et al. (2000) studied the effect of organic manure application in annual crop and perennial pasture systems and reported that manure application improved SOC in annual crop fields compared to perennial pastures. The use of perennial crops in the rotation could improve soil health and SOC levels (Spargo et al., 2011; Delate et al., 2013). However, studies have suggested that harvesting or removal of crop residues may limit the ability of perennial crops to increase SOC (Bell et al., 2012). In the US, Rui et al. (2022) reported that perennial pasture managed with rotational grazing was the only treatment that supported MAOM-C and SOC accumulation compared to annual grain systems.

The literature directly addressing the effects of organic management on pastures is sparse. Schulz et al. (2014) observed a negative effect of no-till organic crop production on SOM levels after 11 years, compared to mixed cropping. They also concluded that perennial legume leys should be included in organic crop rotations to maintain SOM. In northern England, Zani et al. (2021) investigated the effects of organic and non-organic (conventional) farming systems on soil quality indicators on a mixed commercial farm and found that when grazing was included, both conventional and organic systems benefited from significantly improved soil quality. The length of pasture leys in the rotation was positively related to SQ regardless of the type of farming system, and a grass-clover ley length equivalent to 30-40% of the full crop rotation is required to linearly increase soil C concentration. In a horticultural context, Bilenky et al. (2024) found that integrating chickens has the potential to improve soil health indicators such as microbial biomass without affecting the productivity of organic vegetables.

The use of raw manure in food production may pose a risk of E. coli and Salmonella contamination. Bilenky et al. (2024) found no pathogens on the spinach crop when the leaf surface was exposed, even though the pathogens were present in the field after chicken integration. The dynamics of disease regulation in the Canadian beef production industry is also a concern in Canada (Pogue et al., 2018). In Canada, raw manure must be incorporated into the soil at least 120 days prior to harvest if the edible portion of the crop is in contact with the soil, or at least 90 days prior to harvest for all other food crops. Grazing crop residues could reduce the risk of disease from pathogens while improving soil health. In a review, Rakkar and Blanco-Canqui (2018) reported that residue grazing has less negative impact on wind and water erosion than residue baling and less negative impact on soil properties than grassland grazing.

Conclusion

While there is a large literature resource on the effects of organic farming on SOC, few global studies have examined the effects of organic farming on other chemical, physical, and biological parameters of soil health. Research conducted in the Canadian context, particularly for horticultural crops, is also lacking when considering soil health. Compared to conventional production, most studies suggest that organic management can maintain soil health and SOC. This is especially true when best management practices are used and combined in organic systems. These practices include reduced tillage intensity and frequency, cover crops, forages, and integration of livestock into the system. Farming practices in organic systems vary widely in intensity (Lynch, 2022). Therefore, more research is needed to properly assess the impacts of organic management with a variety of practices in Canada's diverse agricultural system.

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2.2 Organic Agriculture and Climate Change Mitigation in Canada

By: Tristin Bouwman

Executive summary

Agriculture is a significant source of greenhouse gas (GHG) emissions, accounting for 10% of the emissions in Canada. To meet Canada's ambitious emission reduction targets the sector will likely need to find ways to reduce its contribution. Organic agriculture, which prioritizes healthy environmental and ecosystem outcomes, may play a role in reducing GHG emissions. Organic agriculture, a certified production system, does not rely on emissions-intensive synthetic fertilizers and pesticides and instead, relies on organic soil amendments, diversification, and biological sources of nutrients which could help build soil health, sequester carbon into soils and reduce emissions. This raises the question, is organic agriculture a potential tool to reduce Canada's greenhouse gas emissions? To help solve this question, this report investigates the likely effects of expanding organic crop production on GHG emissions.

Approach

The primary sources of information used in this report are (1) reviews and life-cycle analyses comparing organic and conventional crop emissions; (2) experimental comparisons of organic and conventional cropping systems on carbon sequestration; and (3) other experiments that evaluate key practices that distinguish organic crop production, namely, reducing pesticide use, green manuring, using manure and compost and increased (secondary) tillage for weed control. Plot-level experimental results cannot always be extrapolated to higher levels of analysis, thus special attention is given to understanding how the expansion of organic agriculture would affect total emissions and food production at higher levels of analysis (i.e. landscape and agri-food system).

Key findings

Organic crops tend to have lower emissions in life-cycle analyses. However, these benefits disappear if total food production is maintained.

- Despite wide variability among life-cycle assessments, organic emissions per ton of food are estimated to be 14% lower than conventional emissions. This result is based on 79 life-cycle comparisons from across the globe of crops relevant to Canadian conditions.
- With lower input use, organic emissions per acre are usually about 35% lower than conventional production. However, organic agriculture produces less per acre. For an equal amount of total production, expanding organic agriculture results in almost no change in total emissions per total production and the potential for significant increases (if production is maintained through the expansion of agriculture).

Organic cropping does not appear to increase carbon sequestration.

- Organically managed soils show higher soil carbon levels. However, these differences can be explained by the transfer and storage of external carbon (particularly manure). Such transfers occur at the expense of soil carbon storage in other locations resulting in no net gain of storage. Manure in Canada is already applied to soil in Canada so organic expansion does not change the amount of manure applied to soil or total soil carbon stocks. Exceptions may occur if: (1) manure is transferred to land that has a higher capacity for storing carbon such soils that are relatively low in soil carbon and heavier textured soils; or (2) (organic) livestock production increases – which could increase total emissions. Where organic agriculture has a high proportion of farmland in perennial cultivation (e.g. 50%), it can be expected to maintain soil carbon better than a system composed of all annual crops.

Using organic amendments is, in general, not a path to reduced emissions.

- The adoption of organic agriculture provides an incentive to reduce synthetic fertilizer use and associated production emissions. However, organic inputs also have carbon footprints. Per unit nitrogen, emissions of common manure-based organic amendments are similar or higher to those of synthetic fertilizers with the exception of solid manure.
- If organic agriculture is expanded using existing organic amendment supplies that would be applied to soil regardless of the production system (e.g. manure and crop residues, other plant-based composts), emissions remain unchanged. However, if expanding organic agriculture affects how these amendments are managed – particularly if freshly applied manure is increasingly composted – emissions may increase substantially.
- Composting results in a more stable carbon source. However, this does not affect the soil carbon stocks compared to the direct application as organic carbon losses during the composting process offset gains from carbon stabilization.

Green manures have limited emissions benefits with high costs

- Medium to long-term legume green manuring studies in Canada do not show increases in soil organic carbon (SOC). There is some evidence that mixed legume green manures increase soil carbon at reasonable rates (e.g. 0.4 Mg/ha/year). Legume green manuring as a nitrogen source is usually not associated with reductions in soil nitrous oxide emissions. Replacing synthetic fertilizer emissions through legume green manures modestly reduces the following crop's carbon footprint through reduced nitrogen manufacturing emissions. However, this comes at the cost of a full season of crop production.

Tillage impacts on emissions vary

- In Eastern Canada (and in high rainfall or irrigated conditions), no-tillage may result in higher net emissions since no-tillage impacts on soil carbon are negligible and nitrous oxide emissions increase with no-tillage under higher rainfall regimes in Canada. In Western Canadian organic systems, no-tillage in cereal likely lowers net emissions if yields are maintained. Where no-tillage substantially decreases yields (e.g. potato production), no-tillage may reduce carbon inputs and thereby reduce soil carbon.

Reducing pesticide use can have sizeable emission reductions for some crops

- Recent life-cycle analyses investigating the role of pesticides in emissions estimate pesticide use to contribute to 20-50% of the emissions of certain crops such as apples, peppers, field cucumbers and viticulture.

Overall, considering the current differences between organic and conventional production, expanding organic crop production appears unlikely to reduce emissions in Canadian agriculture. Many of the differences between organic and conventional agricultural systems at low levels of analysis disappear at higher levels of analysis. Growth in the organic sector that targets individual crops with lower emissions may show some promise with grapes, barley and possibly potatoes appearing to be best-bet candidates. Growth of perennial organic rotations in areas showing soil carbon decline due to conversion from annual to perennial cultivation would prevent soil carbon losses. Similarly, crops with high pesticide requirements in conventional production, or organic food that is already grown elsewhere and is imported over long distances may also be good opportunities for low-emissions growth. Going forward, reducing the yield gap and increasing the emissions difference between organic and conventional agriculture would make the case for using organic agriculture as a tool to reduce emissions more attractive.

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Introduction

Canada's agricultural carbon footprint is 54 megatonnes (Mt) of carbon dioxide equivalent per year (CO_2e), or 8% of Canada's emissions (Environment and Climate Change Canada, 2023). It primarily comprises enteric fermentation from cattle (as methane), manure management (methane and nitrous oxide), and soil nitrous oxide emissions. Agricultural net emissions climb to 72 Mt when machinery and fertilizer manufacturing are included – and they are up 38% from 2005 (Qualman & National Farmers Union, 2022). With global food demand rising (van Dijk et al., 2021), Canadian agriculture cannot continue to play its role in helping meet global food demand and contribute to national emissions reduction commitments unless the carbon intensity and footprint of Canadian agricultural products is reduced. Indeed, the current trajectory indicates further increases (Qualman & National Farmers Union, 2022).

Reducing the carbon footprint of Canadian agricultural products can be achieved by reducing emissions and/or by sequestering carbon from the atmosphere into the soil. No-tillage and reduced tillage, for instance, is estimated to sequester 5.1 Mt annually (Qualman & National Farmers Union, 2022). Organic agriculture is a certified production system that excludes the use of synthetic inputs (e.g. synthetic pesticides and fertilizers), and genetically modified organisms while placing a strong emphasis on soil health, biodiversity, and animal health.

Organic agriculture may offer both emissions reductions and carbon sequestration benefits, since:

1. Organic agriculture does not use synthetic fertilizers and petrochemical-based pesticides. Synthetic nitrogen fertilizer production and application emissions are a major source of agriculture-related emissions, estimated at 22.2 Mt CO_2e annually (Qualman & National Farmers Union, 2022).
2. Organic agriculture instead uses organic inputs, which contribute to SOC and soil health.
3. Organic farming is also committed to ecological practices, which may contribute to climate change mitigation. For example, Canadian organic farmers have double the adoption rate of shelterbelts, four times the adoption rate of green manures, and 1.5 to 3 times higher adoption of cover cropping (depending on farm size) compared to conventional farmers (Klassen, 2022).

Recent Canadian studies have estimated how principles close to those of organic (i.e. nature-based solutions and certain beneficial management practices) could significantly reduce Canada's emissions (Drever et al., 2021; Farmers for Climate Solutions, 2022). However, no study has focused on answering the question: could expanded organic agriculture serve as a tool to reduce Canada's agriculture emissions?

The impacts of organic agriculture on GHG emissions has been a topic of study since at least the 1990s. The current available body of evidence includes numerous modelling studies comparing emissions of organic and conventional commodities (life cycle analyses being the most common), results of long-term trials comparing organic and conventional practices, and results of experiments comparing individual components of organic and conventional systems. As this research has been done across the planet, care needs to be taken in applying the results to the Canadian context. Canada's production systems range widely (e.g. semi-arid to temperate rainforest). However, a key defining factor is their northerly climate, defined by short growing seasons and cold winters. This study focuses on Canadian evidence where possible and evidence from other temperate climates and global results where needed. Finally, most research has been performed at the plot- and farm-level. Since climate change is a global issue and organic and conventional systems are linked by nutrient flows, and both serve the global food system, careful attention is given to where system boundaries are placed in making comparisons (Kirchmann et al., 2016). In this report, careful attention is given to discussing how empirical results of lower levels of analysis (e.g. plot and farm level results), can be expected to relate at a national or global level. This report is divided into four parts:

Part (1) draws on earlier reviews of the topic and life cycle analyses to explore systematic comparisons of organic and conventional farming in terms of net greenhouse gas emissions. It also extrapolates these results to the Canadian context to estimate the impacts of expanding organic agriculture.

Part (2) draws on experimental and modeling evidence to determine whether organic agriculture has carbon sequestration benefits.

Part (3) explores how the key practices of organic agriculture affect emissions:

- Part (3a) explores how replacing synthetic nitrogen with legume green manures impacts carbon sequestration and greenhouse gas emissions.
- Part (3b) explores whether replacing synthetic nitrogen sources with organic nitrogen sources reduces emissions.
- Part (3c) investigates the role of pesticides in emissions.
- Part (3d) investigates how tillage practices in organic systems affect emissions.

Part (4) provides an overall summary and interpretation of the evidence and conclusions.

Part 1: Systematic GHG Comparisons of Organic and Conventional agriculture

1.1 Prominent reviews

Systematic comparisons of the climate change impacts of organic and conventional agriculture date back to at least the 1990s. Stölze et al. (2000) (at Hohenheim University) summarized the state of research at the turn of the millennium for the European Commission. At that point, a handful of studies had compared organic and conventional systems in terms of GHG emissions. These studies suggested lower CO_2 emissions from organic production (wheat and potatoes) per unit area; however, results were variable when reported on a per-unit production (mass) basis. This distinction between functional units – results per unit production (on a mass basis) and per unit area is important. A product grown in a lower input intensity system may simply lower emissions per hectare and lower production per hectare by the same amount, resulting in no change in emissions per unit produced. Thus, a key question is whether organic products themselves have lower emissions intensities than their conventional counterparts – reporting on a mass basis answers this question. Note, that these studies only quantified CO_2 emissions. At that time, the information needed to compare emissions of the other important agricultural greenhouse gasses (nitrous oxide and methane) in organic and conventional systems was scant (Stölze et al., 2000). Nitrous oxide (N_2O) and methane (CH_4) are more potent (~300 x and 25x respectively) and have different lifetimes in the atmosphere (Fuglestvedt et al., 2003).

In 2011, the state of knowledge had advanced significantly. Lynch et al. (2011) analyzed about 130 studies that compared farm-level energy use and global warming potential (GWP). GWP is the combined GHG emissions (i.e. CO_2, N_2O, and CH_4) on a CO_2 equivalence basis normalized over the long term (typically 100 years). Despite the progress made, Lynch et al., (2011) still concluded that the evidence available comparing GHG emissions for organic and conventional systems was insufficient except in a few sectors, with results per ha more consistently favouring organic farming than GWP per unit product.

In 2012, Tuomisto et al., (2012) published a meta-analysis on European research. They reported higher soil organic matter (SOM), and lower nutrient losses per unit area for organic production. However, nutrient losses (ammonia, nitrogen leaching and N_2O emissions) were higher for organic systems per unit mass produced.

In 2017, Clark and Tilman (2017) published an updated meta-analysis comparing organic and conventional agricultural emissions. This analysis compiled life-cycle analyses (LCAs), studies that evaluate the impacts of production from cradle (e.g. upstream input manufacturing) to farm-gate or beyond farm-gate (e.g. consumption). Using LCAs to compare organic and conventional production systems ensures that upstream emissions (e.g. synthetic fertilizer and pesticide manufacturing emissions) are accounted for. They reported that, "Organic systems require [25%-100%] more land, cause more eutrophication, use less energy, but emit similar greenhouse gas emissions (GHGs) as conventional systems." The emissions results were based on 44 LCAs. Organic production emissions were similar to conventional emissions for most food types (i.e. cereals, pulses and oil crops, vegetables, dairy and eggs and meats). However, organic fruits were noted to have lower emissions than conventional fruits.

Most recently, Boschiero et al. (2023) analyzed 77 paired LCA studies comparing organic and conventional cropping systems. Most of the LCAs analyzed were published after 2017 – a testament to the burgeoning field of LCAs. They concluded that organic systems overall performed better than conventional systems in terms of climate change (i.e. greenhouse gas emissions in CO_2e), as well as for ozone depletion, ecotoxicity, human toxicity, acidification, eutrophication, use of resources, water, and energy. The results held both on a per area and per unit mass produced.

1.1.1 Understanding why organic emissions are lower in LCAs

Boschiero et al. (2023) report that on a per unit mass basis, organic GHG emissions were lower than conventional emissions in 73% of cases. However, Boschiero et al. (2023) did not explain the differences between organic and conventional emissions. An exception is rice where they mention that the decomposition of residues in organic rice production results in high methane emissions that do not occur in conventional systems (where residues are burned). A possible explanation for the lower emissions in organic systems could be higher carbon sequestration rates. However, only six studies included evaluations of SOC, indicating that carbon sequestration is unlikely to drive the differences.

How are nutrient production emissions compared?
Boschiero et al. (2023) reported the largest source of emissions in each study (so called 'hot spots'). For conventional production, fertilization was the largest source in 67% of cases, and machinery in 12%. The remaining categories included energy and fuel, chemicals, field operations. For organic production, fertilization was the largest source in 34% of studies and machinery in 28% of studies, while the remaining categories are the same as conventional. With fertilization more often being the largest source of emissions in conventional systems, it may be that fertilization explains the lower emissions for organics. This raises questions about how emissions from nutrient production are compared between organic and conventional systems, specifically, how organic nutrient production is treated if synthetic fertilizer manufacturing emissions are included.

Boschiero et al. (2023) report that most of the studies reviewed included manure transport, composting and application emissions but excluded manure production. Since manure production is a large source of emissions and nitrogen in manure may even be of synthetic origin, fertilization emissions are often not fully accounted for in organic components of LCAs. This is despite recommendations by the United Nations Food and Agriculture Organization (FAO) to include manure as a co-product (i.e. allocate some livestock emissions to manure and thereby crop production) where it is recognized as a valuable product (FAO, 2016; Ledgard et al., 2015; Leip et al., 2019). Organic systems using manure often rely on manure as a valuable, if not critical nutrient source, indicating some livestock emissions should be allocated to manure co-products. Such allocations for manure co-products can be done on a digestibility basis or potentially on a nutrient basis (Leip et al., 2019). Four of the 77 LCAs in Boschiero et al.,'s (2023) review did consider the emissions associated with manure production. When these four studies excluded manure production, the crop production emissions in these studies decreased by 2-12%.

Does nitrogen use explain the differences?
The declines in emissions per unit of production in Boschiero et al. (2023) could be explained by differences in nitrogen use between organic and conventional systems in the LCAs that are not valid for the Canadian context. Since nitrogen is commonly limited in organic systems, we can assume over-application of nitrogen in organic systems is uncommon. However, the over-application in conventional systems in countries with LCAs is rampant. The weighted average of the nitrogen surplus across the countries reported by Boschiero et al. (2023) can be calculated using data from Lim et al. (2024). This weighted N-surplus average, of the countries in which the Boschiero et al. (2023) LCA were performed and for which N-surplus data is reported in Lim et al. (2024), is approximately 90 kg N per ha. However, Canada's N-surplus (although increasing) is estimated to be very low (35 kg N per ha by Lim et al. (2024) and 14.5 kg per ha by Yang et al. (2024)). Since nitrogen fertilization was the largest source of emissions reported in conventional crop LCAs and not in organic crop LCAs, and organic nitrogen emissions factors are not inherently lower than synthetic nitrogen emissions factors (Charles et al., 2017; Walling & Vaneeckhaute, 2020), the reduction in emissions for organic agriculture may be explained by a reduction in N overapplication. If this is the case, it is unlikely that Boschiero et al. (2023) reported

emissions reductions would occur in Canadian agriculture since Canada's N-surplus is already low.

Alvarez (2022) showed that organic-conventional paired trials generally have higher nitrogen use rates in the conventional cereal crops. However, rates were similar for vegetable production. The Boschiero et al. (2023) LCAs cover both trials and actual farm results meaning the extent to which differences in N rates explain the results is difficult to determine.

1.2 LCA results relating to crops commonly grown in Canada

Despite the potential limitations discussed above, Boschiero et al.'s (2023) paired LCA comparisons of organic and conventional products are one of the best sources of evidence in understanding how organic cultivation impacts emissions. In this section, the Boschiero et al. (2023) dataset is updated and investigated. The results are used to estimate how Canada's agricultural emissions might change if organic agriculture is expanded.

1.2.1 Refining the dataset

Boschiero et al.'s (2023) meta-analysis covers 33 countries and numerous crop types – including crops not grown in Canada such as tropical fruits. Over half of the GHG emissions results were from European countries, only two were from Canada, and one was from the USA. The results were reported both in absolute and relative terms. Absolute differences in emissions between systems can be expected to be location-dependent (e.g. soil texture, rainfall, and intensity of inputs). However, the relative differences between organic and conventional agriculture (i.e. difference as a ratio or percentage) offer more broadly applicable insights into how emissions differ between the two systems.

To improve the dataset, several relevant missing LCA outcomes were added to the meta-analysis including a Canadian study on grains by Pelletier et al. (2008). Outlier LCAs (those with a five-times or more difference between organic and conventional systems), were identified and excluded if 1) the difference could be explained by external carbon being concentrated in one production system (See Part 2), or 2) the LCA focused on a specific aspect of production with limited applicability (e.g. only fruit from young trees or systems with and without biogas production). A full explanation of the adjustments made is detailed in Appendix 1.

1.2.2 LCA results relevant to Canadian agriculture

The results of the refined dataset are plotted on a per unit-mass basis in Figure 1. Figure 2 shows the comparison on a per-unit area basis. In the figures, each LCA outcome is a coloured point. The dotted black line represents parity where the impact of organic and conventional are equal. Points below the black dotted line show organic crop production has lower emissions than conventional production. The average and 95% confidence intervals were calculated on natural log-transformed data and back-transformed. Confidence intervals were calculated using the two-tailed t-test method on the LCA outcomes – they do not include LCA outcome uncertainties. For crop types with less than five results, confidence intervals were not calculated.

As shown in Figure 1, LCA results show organic products tend to have smaller carbon footprints. Among the 79 paired LCA results, organic products had lower emissions than conventional in 70% of cases. On average the carbon footprint of organics was 14% lower than conventional (95% confidence interval range of 3% to 24%). The average response ratio of the original Boschiero et al. (2023) data without exclusions or inclusions is also a 14% reduction[1].

Certain organic crops such as barley, grapes, and possibly potatoes had results which were systematically lower than conventional production. Other crops, most notably apples, had consistently higher emissions. However, this trend may not apply in Canada since an LCA on apples has been performed in Eastern Canada and shows only a 2% increase in emissions per kilogram for organic apples (Keyes et al., 2015).

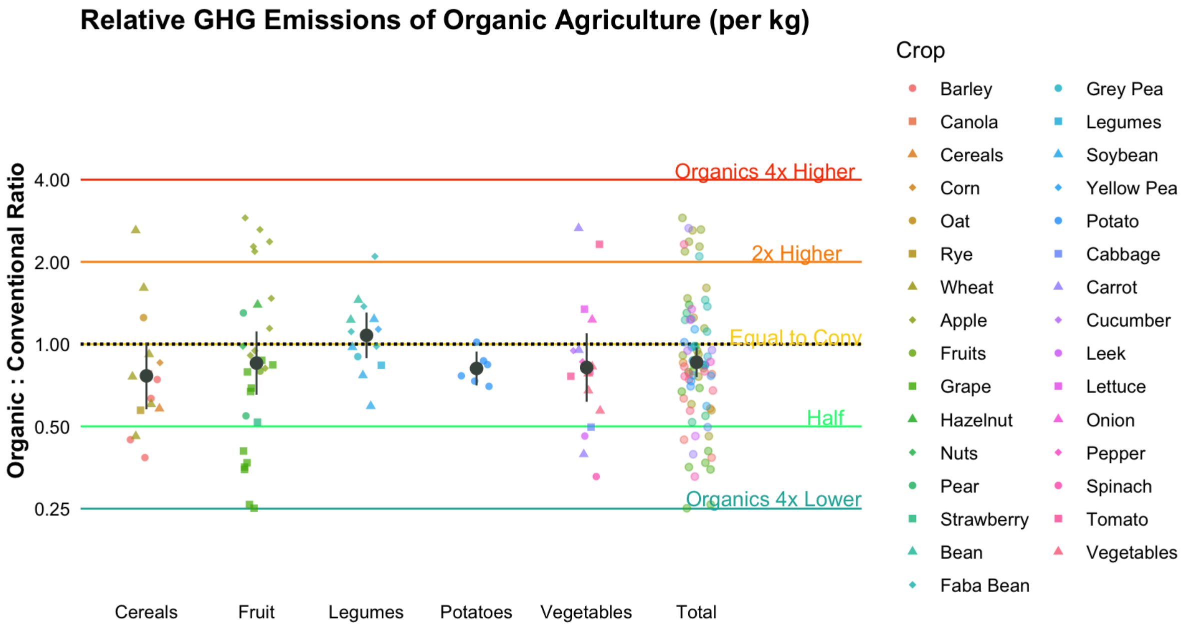

Figure 1: Relative greenhouse gas emissions of organic agriculture compared to conventional agriculture on a per unit mass basis by product and product type. Each coloured points is an LCA outcome. Black point ranges are the average and t-test 95% confidence intervals. Data adapted from Boschiero et al., (2023).

Figure 2 shows organic emissions are also lower than conventional on a per unit area basis (e.g. per acre). Overall LCA emissions per unit area were 34% (95% confidence interval of 19-46%) lower for organic farmland (n=36). While emissions per acre were lower, it is worth noting that the land area required for organic production was reported in 32 studies and was on average 35% higher. The higher land requirements correspond directly with reduced yields in organic systems which averaged 26% lower across the dataset.

[1] Calculated by log transformation of the original data after adding a constant of the minimum value plus one. The choice of constant used strongly affects this result with lower constants favouring the very low and negative response ratios and favouring lower emissions in organic production.

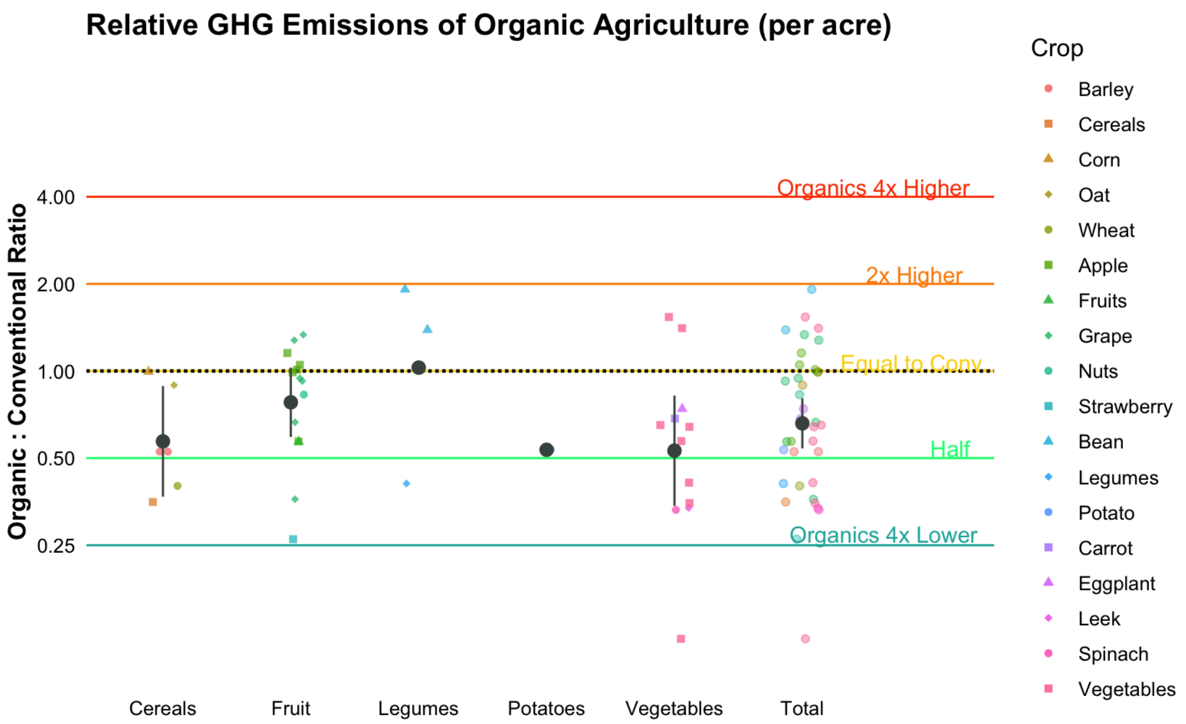

Figure 2: Relative greenhouse gas emissions of organic agriculture on an area basis. Coloured points are study outcomes. Black point ranges are the average and 95% confidence intervals. Ranges are only calculated when n>5. Data adapted from Boschiero et al., (2023).

1.2.3 Scaling the results to the agri-food system level

When scaling this crop-level data to the landscape level, it is critical to account for the production changes properly to ensure fair comparisons between production systems (Kirchmann et al., 2016). Yield-scaling emissions per crop (i.e. accounting for changes in comparative yield by reporting LCA results on a per unit mass basis rather than per unit area basis) is the first step. However, to scale to the landscape level, farm-level productivity changes need to be accounted for (i.e. differences in harvested area per farm). To scale from the farm-level to the landscape level, food system-level changes in productivity need to be accounted for if total food production can be expected to be maintained. This section describes how emissions differences from expanded organic agriculture expand as the level of analysis and system boundaries expands.

1.2.4.1 Yield scaling emissions by crop

Since most LCAs already report emissions on a per unit mass basis, the majority of the Boschiero et al. (2023) data are already yield-scaled. On average, the yield difference reported in these LCA's was a 26% reduction in production for organic. This value aligns with other meta-analyses of organic and conventional yield differences (e.g. de Ponti (2012) and Alvarez (2022)). The recent Alvarez (2022) meta-analysis reported a 25% average reduction in paired crop comparisons. A 26% reduction in yield explains the difference between emissions per unit mass produced (15% reduction for organic) and per unit area (34% reduction for organic).[2]

[2] (1-0.15)*(1-0.26)= 0.63 or a 37% reduction in emissions – very close to the reported overall reduction of 34%.

1.2.4.2 Scaling to farm-level emissions

In organic production, parts of the rotation are often dedicated to green manures. This affects the area harvested at the farm-level. Alvarez (2022) reported that across 84 on-farm organic-conventional comparisons, the intensity of soil use (the portion of the crop rotation in which crops were harvested) was 20% lower in organic systems. (The reduction was less in trials, but trials do not represent farmers' practices as well as actual farms). A 25% reduction in yield with an average area out of production of 20% results in a 40% reduction in overall production. A recent analysis by Connor (2024) at the farm-level rather than plot-level yield pairs found even larger reductions (i.e. 50%) are common on organic farms.

The impact of green manuring on emissions needs to be estimated at the farm-level of analysis. Green manures are generally used to provide nitrogen through biological nitrogen fixation. Rochette and Janzen (2005) showed that legume cultivation has similar N_2O emissions to background N_2O emissions. Generously, assuming there are no major additional emissions involved in green manure production, the green manure portion of organic farms can be assumed to have negligible emissions. Thus, scaling up to the farm-level increases the difference in food production and the reduction in emissions between organic and conventional systems.

1.2.4.3 Scaling to landscape and current agri-food system

So far, we have partially accounted for yield differences between organic and conventional production by yield-scaling the emissions. However, the overall decline in production indicates a comparison of a lower and higher production system. Thus, one needs to calculate the impact on emissions of organic expansion for an equal amount of total food production for a fair comparison. This is especially the case in the context of a need for increased total food production. A meta-analysis of projections by Van Dijk et al. (2021) shows that food supply is projected to need to increase by 35-56 percent by 2050 to meet global demand (depending on the various scenarios, but not considering climate change). Productivity declines from expanded organic agriculture can thus reasonably be expected to be compensated for elsewhere in the food system. Compensation can occur through increased conventional production per unit of land or expansion of agriculture by converting natural vegetation to agriculture. In Canada alone, an estimated 22,000 ha of forest and 250,000 ha of grassland are converted to agriculture annually (Drever et al., 2021; Environment and Climate Change Canada, 2023). Conversion of natural vegetation to agricultural land has important emissions implications. For example, Flynn et al. (2012) estimated average land use change emissions for conversion from natural vegetation to soybeans and rapeseed. Values for Canada were 17 Mg CO_2e per hectare per year (over 20 years) - a typical value for the 20 countries they considered. This value is about an order of magnitude higher than agricultural production emissions. For example, average cereal production emissions in Canada are estimated at 1.45 Mg CO_2e per ha per year (Clearwater et al., 2016).

Scaling the results in the context of future, alternative food systems is beyond the scope of this study. A global transition to nutritionally balanced diets would increase emissions unless the new diet is a low-livestock protein diet (Kc et al., 2018). Reducing food waste, reducing per-capita caloric intake or transitioning to low-livestock protein diets could enable the expansion of organic agriculture without compensation elsewhere in the food system

(Barbieri et al., 2021). In such a situation, the benefits of expanding organic agriculture would have to be compared with reducing the land area of conventional agriculture. Considering the need for increased food demand is expected to be a serious challenge in creating a zero-hunger future, losses in food production from organic agriculture can be expected to need to be compensated for in the near to medium term.

1.2.4.4 Putting the pieces together

Figure 3 explores how expanded organic agriculture (from 0% to 25% of a hypothetical landscape) impacts emissions and production. The following is assumed:

1) A 35% reduction in emissions per unit land area (as per Boscherio et al. (2023))
2) A 25% reduction in yield per acre (as per Alverez (2022) and Boscherio et al. (2023))
3) A 15% reduction in emissions per unit produced (as per Boscherio et al. (2023))
4) A 20% reduction in harvested area due to green manure production (as per Alverez (2022))
5) The reduced harvested area (green manures) emissions are similar to background emissions and are, therefore, negligible (Rochette & Janzen, 2005). No carbon sequestration is assumed in the organic system (see Part 2).
6) Conversion of land to agriculture results in a 10-fold increase in emissions over 20 years (comparing Clearwater et al. (2016) emissions per ha with Flynn et al. (2012).

The figure shows how accounting for changes in production strongly affects the overall emissions. In the case where emissions per acre are used to scale emissions, a 25% increase in the organic agriculture area can reduce emissions by 9% (Scenario B). Accounting for the change in harvested area further reduces emissions to a 12% reduction (Scenario C). However, the total emissions per total amount of food produced only changes marginally (2% reduction). Thus, most of the emissions reductions come from reduced food production. If conventional and organic production increases to compensate for production losses with current emissions intensities, the total emissions reductions are mostly erased – resulting in only a 2% reduction in total emissions (Scenario D1). If production losses are compensated for through expansion of agriculture, the situation worsens considerably by doubling total emissions (Scenario D2). The tenfold increase in emissions on 0.4 units of land results in nearly doubling total emissions. On an incremental basis, maintaining production losses from converting conventional land to organic production by expansion of agriculture means every hectare converted to organic agriculture results in 0.4 ha of agricultural expansion. The 10-fold increase on this 0.4 ha from land use change combined with the crop production emissions on the 0.4 ha and a 50% reduction in emissions on the newly converted organic land translates into a fourfold increase in emissions compared with no conversion.

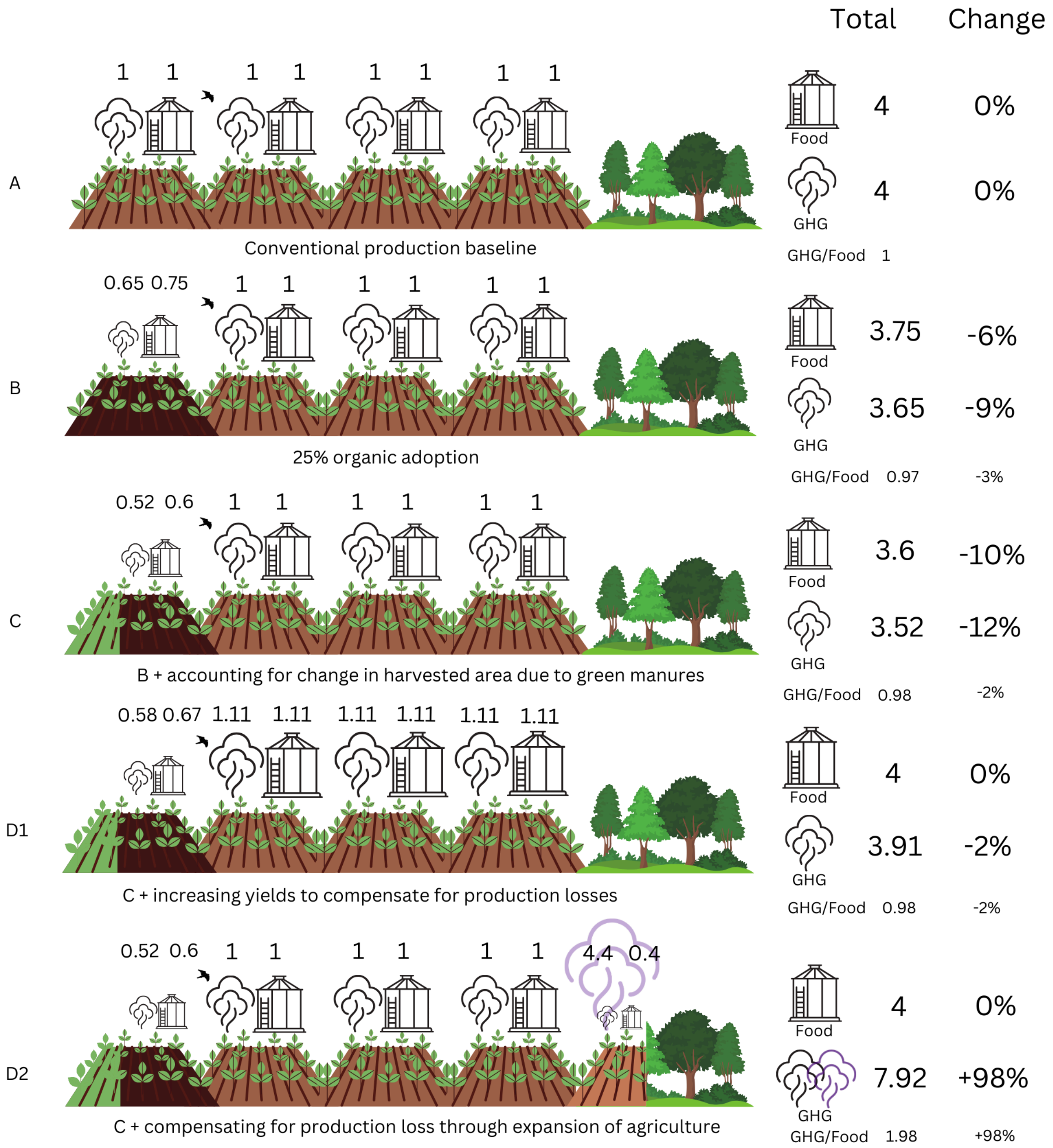

Figure 3: The impacts of expanding organic agriculture on (agri-)food production and greenhouse gas (GHG). Scenarios (B-D) increasingly account for the impacts of changes in production – from yield changes (B) to changes in harvested area due to green manures (C) to compensating to maintain overall food production (D).

The emissions increase on an equal total food production basis echoes findings of a modelling study by Smith et al. (2018). They reported that domestic emissions would be reduced by country-wide adoption of organic agriculture in England and Wales. However, when changes in overseas land use needed to compensate for declines in domestic food production were factored in, total emissions increased.

1.2.4.5 Scaling to the Canadian landscape (simplified extrapolation)

The impacts of organic agriculture on emissions at the landscape or global level strongly depend on how total food supply needs are met. This section considers how emissions might change if LCA data are scaled without considering how production changes might be compensated for or accounting for green manure effects on production and emissions (Scenario B in Figure 3). Boschiero et al.'s (2023) results can be extrapolated on a per acre basis or on a per unit mass basis (after accounting for yield changes). On aggregate, this produces very similar results (e.g. 15% reduction in emissions per unit yield after a 26% reduction in yield works out to a 36% reduction – very close to the 34% per acre functional unit reduction). Extrapolating using per-unit mass LCA data uses a larger data set (e.g. 32 LCA outcomes vs 82), however, differences in yield do need to be accounted for.

National crop emissions for organic and conventional agriculture are estimated using the emissions per unit mass (i.e. per unit yield) data which are then adjusted by the change in yield for that crop (Table 1). In addition, Table 2 estimates crop emissions for organic and conventional agriculture using the emissions per unit area data. Table 1 reports estimates for Canada's main crops (wheat, barley, oats, rye, canola, flaxseed, pea, lentils, chickpeas, corn, soybeans and potatoes), as well as a selection of horticultural crops which show promise for organic expansion indicated by a large trade deficit or reports showing potential for expansion by the Canadian Organic Growers (See Appendix 2 for a full explanation of the calculations and assumptions). Table 2 only reports estimates for crops for which there are per unit area emissions estimates reported by Clearwater et al. (2016). Both Tables rely heavily on Canadian crop emissions factors reported in Clearwater et al. (2016). These values are in the process of being updated, which may affect the overall results. Both tables also estimate the impact of a three-fold expansion of organic agriculture on emissions.

As shown in Table 1, a three-fold increase in organic crop production in Canada could be projected to reduce emissions by 368 thousand metric tonnes of CO_2e – or by about 0.5% of Canadian total agricultural emissions. Table 2 shows a larger emissions reduction. The difference is primarily due to different emissions reduction factors (relative emissions differences between organic agriculture and conventional agriculture from Boschiero et al. (2023)) for wheat and oats. In wheat, for example, the emissions reduction factor is based on six LCAs in Table 1, but only one LCA in Table 2. Overall, using this method of calculation, the impact of a threefold expansion of the organic agriculture crop area can be expected to have very minor effects (0.5-1%) on Canada's total agricultural emissions. This impact may be slightly larger if green manures are taken into account, and much smaller or a net-negative outcome if overall production levels are maintained (see Figure 3).

Overall, the field of LCA suggests that organic crop production tends to modestly reduce emissions on both a per unit mass basis and a per unit area farmed basis. However, for producing an equal amount of food, expanding organic agriculture can be expected to have a very marginally positive impact on emissions at best with a reasonable risk of substantially increasing emissions.

Table 1: Estimates of current emissions and emissions with a three-fold organic area expansion from organic and conventional production in Canada by crop. Emissions differences between organic and conventional are calculated using relative per-unit mass emissions data and relative yield data from Boschiero (2023).

Crop	Area seeded or cultivated (ha)	Dry matter (%)	Average yield (kg DM/ha)	Conventional production (Mg DM)	Current Proportion organic	Organic yield coefficient	Organic production (Mg DM)	Conventional emission factor (kg CO_2e/ kg DM)	Current Conventional emissions (kt CO_2)	Emissions Reduction Factor for Organics	Current Organic emissions (kt CO_2)
Wheat	10,234,572	87%	2,364	23,895,775	1.2%	0.79	234,499	0.40	9,558	0.70	63
Canola	8,869,043	90%	1,863	16,517,596	0%	0.76	4,128	0.78	12,884	0.78	3
Barley	3,060,427	87%	2,727	8,294,527	1%	0.71	36,962	0.43	3,567	0.53	9
Oats	1,372,628	88%	2,734	3,441,275	8%	0.71	222,362	0.53	1,824	1.25	147
Rye	185,727	87%	2,811	481,817	8%	0.76	30,563	0.48	231	0.57	8
Flaxseed	322,121	94%	1,098	330,449	7%	0.76	17,645	0.67	221	0.78	9
Peas	1,385,351	87%	1,789	2,456,727	1%	0.57	12,640	0.38	934	0.84	4
Lentils	1,644,438	90%	1,033	1,682,002	1%	0.57	9,869	0.43	723	0.84	4
Chickpeas	104,081	90%	1,047	91,786	16%	0.57	9,784	0.36	33	0.84	3
Corn	1,500,631	87%	8,697	12,889,720	1%	0.89	144,047	0.44	5,671	0.81	53
Soybeans	2,166,806	89%	2,714	5,761,532	2%	0.80	95,028	0.38	2,189	0.77	31
Potatoes	157,377	20%	8,255	1,262,697	3%	0.73	26,587	0.37	467	0.81	8
Carrots	9,317	11%	4,370	39,633	3%	0.75	817	3.25	129	1.00	3
Lettuce	3,711	10%	2,255	8,192	2%	0.70	125	31.35	257	1.34	5
Spinach	874	9%	801	640	9%	0.76	46	3.50	2	0.33	0
Apples	17,914	16%	3,284	56,960	3%	0.54	998	8.73	497	1.79	14
Blueberries	78,894	17%	2,686	186,605	12%	1.00	25,305	3.89	725	0.78	77

Table 1: Continued

Crop	Current Total emissions (kt CO_2)	Three-fold expansion of organic agriculture – new area (% of total)	Target Organic Area (ha)	Conventional Emissions with target organic area (kt CO2e)	Organic Emissions with target area (kt CO2e)	Total Emissions with target (kt CO2e)	Emissions change with three-fold organic area target (kt CO2e)
Wheat	9,621	4%	377,768	9,320	190	9,510	-112
Canola	12,886	0%	8,746	12,875	8	12,883	-3
Barley	3,576	2%	56,924	3,522	27	3,549	-27
Oats	1,971	25%	341,611	1,494	442	1,936	-35
Rye	240	23%	42,923	193	25	218	-22
Flaxseed	231	20%	63,438	190	28	218	-13
Peas	938	3%	37,245	917	12	929	-9
Lentils	727	3%	50,356	708	11	719	-8
Chickpeas	36	47%	49,269	21	9	30	-6
Corn	5,724	4%	55,827	5,529	158	5,687	-37
Soybeans	2,220	6%	131,102	2,099	93	2,192	-28
Potatoes	475	8%	13,239	440	23	463	-12
Carrots	131	8%	744	122	8	130	-2
Lettuce	262	6%	237	246	16	261	-1
Spinach	2	26%	225	2	0	2	0
Apples	511	9%	1,699	465	42	507	-4
Blueberries	802	36%	28,264	529	230	759	-43
						Total:	**-362**

Table 2: Estimates of current emissions and emissions with a three-fold organic area expansion from organic and conventional production in Canada by crop. Emissions differences between organic and conventional are calculated using relative per-unit area emissions data from Boschiero (2023).

Name	Area seeded or cultivated (ha)	Current conventional emissions rate (kg/ha)	Organic area (ha)	Organic emissions coefficient (per ha basis)	Current conventional emissions (kt CO_2e)	Current organic emissions (kt CO_2e)	Current total emissions (kt CO_2e)	Conventional emissions with 3x organic area (kt CO_2e)	Organic emissions with 3x organic area (kt CO_2e)	Total emissions with 3x organic area (kt CO_2e)	Emissions change (kt CO_2e)
Wheat	10,234,572	1120	125,923	0.40	11322	57	11378	10899	170	11068	-310
Canola	8,869,043	1360	2,915	0.65	12058	3	12061	12046	8	12054	-7
Barley	3,060,427	1120	18,975	0.53	3406	11	3418	3343	34	3376	-41
Oats	1,372,628	1240	113,870	0.89	1561	126	1687	1137	379	1516	-171
Rye	185,727	1030	14,308	0.65	177	10	186	132	29	161	-25
Flaxseed	322,121	850	21,146	0.65	256	12	268	202	35	237	-31
Peas	1,385,351	780	12,415	0.65	1071	6	1077	1042	19	1061	-16
Lentils	1,644,438	570	16,785	0.65	928	6	934	899	19	918	-16
Chickpeas	104,081	580	16,423	0.65	51	6	57	22	19	41	-16
Corn	1,500,631	3030	18,609	0.99	4491	56	4547	4321	168	4490	-57
Soybeans	2,166,806	840	43,701	0.65	1783	24	1807	1673	72	1745	-62
Potatoes	157,377	2620	4,413	0.53	401	6	407	366	19	385	-22
									Total:		**-776**

Part 2: Organic agriculture and carbon sequestration

Organic agriculture has sometimes been posited as a tool to substantially reduce global emissions through carbon sequestration. For example, Scialabba and Müller-Lindenlauf (2010) at the United Nations FAO reviewed the potential impacts of organic agriculture to reduce global agricultural GHG emissions. They estimated that a global transition to organic agriculture would result in enough carbon sequestration to offset 40–72% of the world's annual agricultural emissions. The carbon sequestration rate estimates were based on another FAO study by Niggli et al., (2009) which reported carbon sequestration rates from long-term organic-conventional trial comparison results.

In the context of declining carbon stocks in Eastern Canada (Clearwater et al., 2016), such solutions are desirable. In PEI, for example, SOM is reported to have dropped approximately 18% (from 3.2% to 2.7% SOM) in the last 25 years on potato land (similar declines occurred on oil seeds/grains and forages) (Prince Edward Island Department of Agriculture, 2023). This is a large loss in SOM. For comparison, Canada's soils lost on average 24% SOM when native grasslands were converted to croplands (VandenBygaart et al., 2003).

Since 2009, several global meta-analyses have estimated carbon sequestration rates for organic agriculture. Gattinger et al. (2012) reported an overall result of 0.45 Mg C/ha per year, García Palacios et al. (2018) reported an average of 0.24 and Tiefenbacher et al. (2021) reported an average of 0.29 Mg C/ha. These are large carbon sequestration results, but they require careful interpretation. Lorenz and Lal (2023a) show that carbon sequestration should be distinguished from changes in carbon storage. The key difference is that carbon sequestration refers to additional carbon of atmospheric origins that is added to the landscape. In contrast, carbon storage refers to changes irrespective of origin. In some cases, increases in SOC in soils do not imply removal from the atmosphere but transfer from one carbon pool to another. This occurs when manure is added to the soil of another farming system. Since organic agriculture often relies on external manure sources, carbon sequestration estimates can easily be confounded by transfers of carbon storage. This was illustrated in Gattinger et al.'s (2012) analysis, which reviewed 74 pairwise comparisons of organic and conventional farming. However, after studies were excluded that added more than one European livestock Unit worth of manure, failed to measure bulk density, or failed to include measurements of external C inputs, the difference in sequestration rates fell to 0.07 Mg C/ha/yr and not statistically significantly different from zero.

García Palacios et al. (2018) expanded on Gattinger et al.'s (2012) analysis. They reported an average of 0.24 Mg C/ha/yr for cereals, vegetable orchards, and viticulture when only studies that included low manure rates were included. Similar to Gattinger et al. (2012), they defined low manure rates as being less than one European animal unit per hectare, but this time found a significant increase in soil carbon. It is worth noting that one European livestock unit is equivalent to one dairy cow. Assuming a dairy cow produces 20 Mg of manure per year at 15% dry matter, of which 45% is organic matter consisting of 50% carbon with 25% of C retained in soil, about 70% (0.17 Mg/ha/year) of the 0.24 Mg C/ha/year might still be explained by manure addition. Considering this does not account for carbon in bedding, it is possible that their results can still be explained by manure transfer. García Palacios et al. (2018) did note that the carbon sequestration rate among comparisons with low manure rates was similar to comparisons with higher manure rates. They conclude that crop traits (increased decomposability) result in higher microbial activity and more efficient conversion of plant carbon to SOC.

In 2019, a global meta-analysis of paired comparisons, Smith et al. (2019), found that organic carbon stocks were 11% higher in organically managed systems than in conventional systems. However, this study did not account for external carbon transfers.

More recently, Alvarez (2021) reviewed 83 experimental comparisons of organic and conventional systems in terms of soil carbon. The experiments were separated according to whether: 1) no carbon transfer between systems occurred, 2) carbon transfer occurred between systems (e.g. removal of conventional crop residues or addition of manure to organic treatments) and 3) carbon management was undefined. Where carbon transfer occurred, SOC was 22% higher in organics than in conventional. However, when no carbon transfer occurred, SOC did not differ between systems. Alvarez concluded that organic farming itself does not increase soil carbon.

In 2023, Gaudare et al. modelled the impacts of widespread organic agriculture on emissions. Considering reduced organic carbon inputs in organic agriculture (e.g. 29-39%) due to reduced crop residue production and manure production, global organic carbon stocks would decline by about 9% after 20 years. They conclude that the expansion of organic farming might reduce its potential to mitigate climate change unless appropriate practices are implemented.

Identifying the impacts of organic agriculture on carbon sequestration remains very difficult due to the carbon storage and transfer problem (Lorenz & Lal, 2023b). Considering that when external carbon transfers are fully accounted for, organic system studies show no more soil carbon than conventional, it seems most reasonable to conclude that organic agriculture does not sequester carbon or maintain carbon stocks better than conventional agriculture. Thus, it is unlikely that organic agriculture would significantly affect total soil carbon stocks in Canada. There is also a risk that organic agriculture would result in carbon losses due to reduced plant residue levels from reduced yield, depending on how green manures and cover crops offset these losses. Finally, it should be noted that changes in organic carbon levels can be assumed to be short-run, not long-run changes as the effects attenuate over time as a new soil carbon equilibrium is reached (Moinet et al., 2023). Indeed, in the long-run carbon sequestration in agriculture in general seems unlikely to play a significant role in mitigating climate change (Moinet et al., 2023).

2.1 Organic agriculture as a strategy to address declining soil carbon stocks in Eastern Canada

As shown in Figure 4, carbon in Canadian agricultural soils is in a state of flux. In general, Western Canadian soils are gaining soil carbon, while Eastern Canadian soils are losing soil carbon. Overall, Canadian soils are sequestering carbon. Expanded organic agriculture adoption may affect these fluxes.

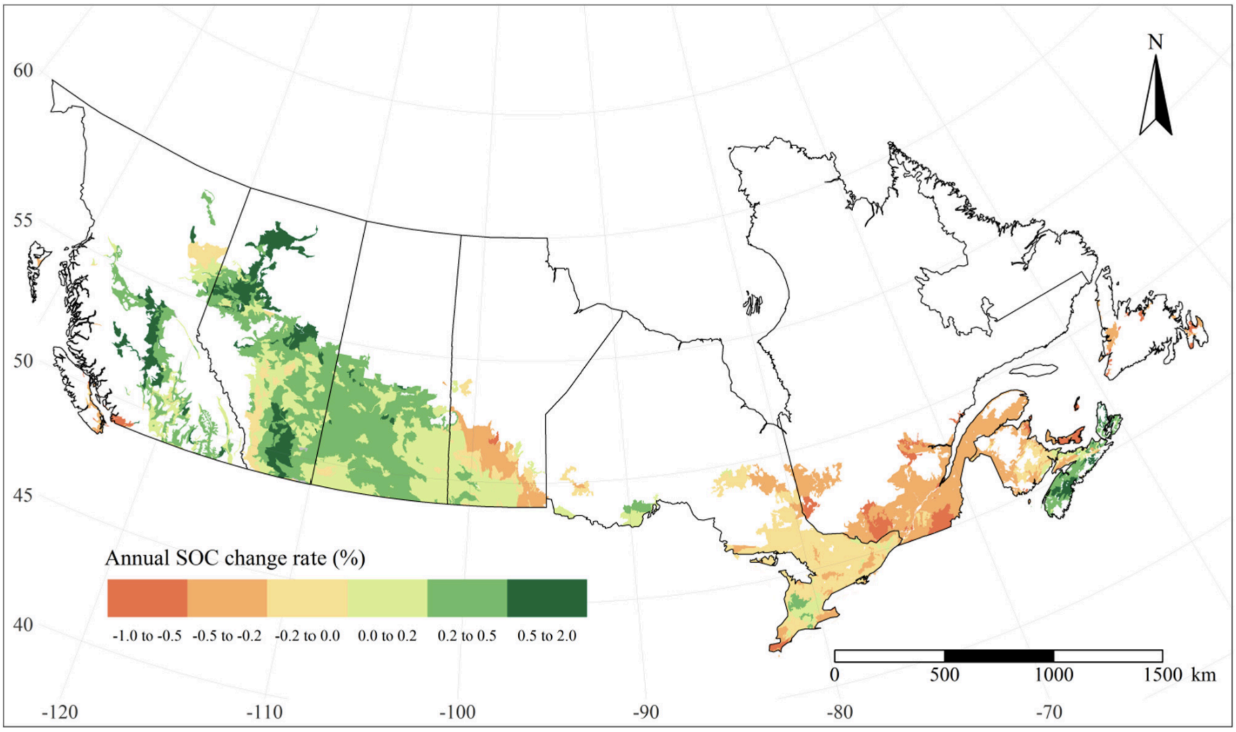

Fig. 4. Annual rate of change of SOCs (%) from 1971 to 2015 in 0–20 cm soil depth across Canada.

Figure 4: Annual rate of change of Soil Organic Carbon from 1971 to 2015 in the top 0-20 cm across Canada (As seen in Fan et al. (2019).

The increases in soil carbon in Canadian agriculture overall are mainly due to "increases in crop yield, [with an] enhanced C sink since 2005 reflect[ing] increasing C input largely driven by the increasing area and yield of canola" (Fan et al., 2019). High-yielding canola production has largely displaced the practice of summer fallowing, which does not provide carbon inputs to soil, in Western Canada.

Losses of soil carbon in Eastern Canada appear to be driven by the decline of pasture and forages and increases in cereals in oilseeds (Canada, 2016). This shift is in part attributed to the decline of cattle production in the region following the BSE crisis of the early 2000s (Canada, 2016). The area of annually seeded crops has expanded from 2.3 million ha in 1980, to 3.9 million ha in 2020 in eastern Canada. The area of tame hay (predominant perennial) decreased from 2.4 million ha to 1.4 million ha during the same period. The location of intensive cropping has also shifted as prime agricultural land has been lost. From 1971 to 2011, 0.7 million ha was lost to settlements in Eastern Canada, 74% of which was Class 1 to 3 land. It follows that the total area of farmland converted to cropland exceeds the net increase of 2.3 million to 3.9 million ha.

How expanded organic crop production would affect the resulting trends in soil carbon depends largely on how organic farming affects carbon inputs per crop and how organic farming affects the proportion of land under pasture and forage production versus annual crop production (e.g. cereals and oilseeds).

On a comparable crop basis, carbon input levels in organics are generally lower due to lower yields (e.g. 25% lower (Alvarez, 2022; Boschiero et al., 2023). However, this estimate is likely to vary by crop and be affected by differences in carbon inputs from weeds. Organic agriculture may not be intrinsically less intensive in terms of arable crop production compared to perennial grasslands. However, organic systems may enable the viability of high inclusion rates of perennial crops and/or green manures (grass or legume mixes) which can add more carbon inputs than an annual crop rotation and help sustain soil carbon in Eastern Canada. High green manure or forage inclusion rates (e.g. 50% or more of a crop rotation), can be expected to overcome declines in carbon inputs from reduced yields and help to prevent further losses of organic carbon.

Part 3: The impact of organic practices

3.1 Green manures, biological nitrogen fixation and emissions

Organic growers often rely on green manures to improve soil health and SOM, and to serve as a source of nitrogen. This practice is common on Canadian organic farms. Approximately 45% of Canadian organic growers report using green manures, more than 4x the proportion of non-organic certified growers (Klassen, 2022). Green manures are crops that are not harvested for market, but instead retained in the field to add fertility to the subsequent crop. In this analysis, they can be distinguished from cover crops in that cover crops are grown to ensure bare land is covered (particularly after harvest and through the winter). Legumes, crops capable of biologically fixing nitrogen, are often grown as green manures in organic systems as a source of nitrogen for the subsequent crop(s).

Green manures may be an important tool for reducing Canada's agricultural GHG emissions. They could do so: (1) by increasing carbon sequestration, since they increase soil carbon inputs, (2) since leguminous green manures are used to replace synthetic fertilizer needs, reducing fertilizer manufacturing emissions, (3) as an organic source of nitrogen, N_2O emissions from the green manure (crop residues) may be lower than synthetic nitrogen sources. In the following sections, each of these pathways are addressed.

3.1.1 Do green manures increase soil organic carbon?

Changes in SOC levels are the net of carbon additions and losses from the organic matter pool (Lal et al., 2015). Thus, when green manures are sown and the carbon fixed during photosynthesis is not removed by harvest, the SOC pool may increase. However, as illustrated in Canada's long-term trials in the Black Soil Zone, legume green manures may not provide enough carbon to affect the soil carbon pool in the long-term.

Long-term legume green manure trials were initiated in the late 1950s in the Canadian Prairies. In the late 1980s, SOM was compared between a one-in-three-year green manure and continuous wheat in Indian Head and Melfort Saskatchewan. After 30-years, the Indian Head green manure treatments had slightly lower SOM levels in the top 15 cm but were not statistically significantly different from continuous wheat ($p>0.1$) (Campbell et al., 1991a). Similar results were published from the long-term experiment in Melfort, except SOM was statistically significantly lower in the green manure treatment when samples were taken after the green manure crop ($p<0.10$) (Campbell et al., 1991b). When the green manure was sampled in a wheat-producing year there were no statistically significant differences. The Indian Head site was resampled in 1996 on a mass-equivalency basis and this time green manures were slightly higher, but results were again not statistically significantly different ($p>0.05$)[3] (Campbell et al., 1998, 2001). A third, 10-year experiment in Swift Current, reported similar results - no increase in mass-corrected SOC for legume green manure over continuous wheat (Campbell et al., 2000). Four legume green manure species in a one-in-three-year rotation were also compared to continuous wheat in Swift Current with no statistically significant changes in SOM (Biederbeck et al., 1998). These results are not surprising as total crop residue production in Bierderbeck et al., in Campbell et al., (1991b), in (1991a) and crop residue carbon production in Campbell (2000) were similar (i.e. within 15% of each other and not significantly different) between green manure and fertilized continuous wheat rotations.

In Eastern Canada, a short-term (5-year) study was done in Quebec and showed similar results for legume green manures (N'Dayegamiye & Tran, 2001a). Green manures were planted in the first and fifth year and treatments were soil sampled in the fifth year after green manure incorporation. The legume (clover) green manure treatment yielded poorly and showed a small (not statistically significant) decline in soil carbon compared to the control. The non-legume green manures showed large and statistically significant increases. These large increases are likely a result of the short-term effects of the green-manure carbon additions. Where yields were high, these had approximately double the soil decomposition (microbial CO_2 respiration) rates.

Beyond Canadian trials, recent reviews and meta-analyses serve as another line of evidence. These include a meta-analysis by McClelland et al. (2021) of cover cropping (including “summer” cover crops and “continuous” cover crops) on soil carbon; a review of cover cropping studies by Blanco-Canqui (2022) which establishes a relationship between cover crop biomass inputs and SOC change; and a global meta-analysis by Gross and Glasser (2021), of the impacts of manures (including green manures) on soil carbon.

McClelland et al. (2021) evaluated cover crops in seven temperate climate countries (United States, Canada, France, Denmark, Spain, Italy and Australia) and reported that both “summer” cover crops and “continuous” cover crops increase soil carbon. In the Canadian context, a summer cover crop and a continuous cover crop are conceptually similar to green manures with the exception that green manures are usually incorporated into a rotation (e.g. once in three years) while cover crops in experimental contexts are grown each year. These cover crops especially increased SOC when legumes were mixed with non-legumes. The disaggregated results were reported by the authors in their supplementary materials. They show that among the studies analysed, there were no medium- or long-term *year-round* cover cropping trials. There were, however, three medium- to long-term *summer* cover cropping studies (five pairs) in cool, temperate conditions (Allen et al., 2011a; Chirinda et al., 2010; Hansen et al., 2015). The average change in soil carbon of these five pairs measured in the top 25 or 30 cm was a loss of - 0.09 Mg C / ha / year. However, upon closer examination, we find Allen et al. (2011b) are results of a summer fallow- legume green

[3] LSD across various treatments far exceeded treatment differences.

manure comparison in the United States. Both treatments lost soil carbon with the reported loss being slightly higher for the green manure. The difference, however, was not statistically significant. This is a surprising result as summer fallows usually result in soil carbon losses which green manures are usually able to mitigate (VandenBygaart et al., 2003). Chirindra et al., (2010) reported higher soil carbon after 11 years in an organic rotation with a grass-clover green manure in two locations in Denmark. One location showed a statistically significant increase (4 or 8% increase in soil carbon depending on whether cover crops were included) and the other was not statistically significant. Results from these locations of this Danish experiment are further reported by Hu, et al., (2018). In their publication, green manures significantly increased soil carbon content in both locations during the years in which none of the green manure was removed. Both treatments in this comparison were managed organically. On average, this resulted in a 19% difference in SOC over 6 years implying the green manure contributed 0.4 Mg/ha/year. Finally, in Denmark, Hansen et al., (2015) found no changes in SOC concentration in rotations where spring annuals and catch crops replaced winter annuals. Thus, the relevant comparisons from the McClelland et al., (2021) meta-analysis provide results similar to the Canadian trial evidence - that pure legume green manures do not generally increase SOC. Meanwhile, legume-non-legume green manure mixes may increase SOC.

Another approach to estimate green manure benefits is to apply the results of United States cover cropping research while accounting for biomass inputs. Blanco-Canqui (2022) reviewed US cover cropping data and found that 55 of 77 pairs did not show significant soil carbon increases. Among studies reporting biomass production, SOC increases were only seen when biomass production exceeded 2 Mg/ha. Even when biomass production exceeded this value, SOC still did not significantly increase in 72% of study pairs (n=36). Counting not statistically significant differences as zero, the average change from 2-6 Mg/ha biomass production was 0.07 Mg C/ha/year and the average with biomass production greater than 6 Mg/ha was 0.27 Mg C/ha/year. Green manure yields are not generally collected in Canada, however, in a review of green manures in the Canadian context, Thiessen Martens and Entz (2011) report that typical green manure yields are 2,500 and 5,000 Mg/ha for the Brown and Black soil zones, respectively. Such yields align with Canada's tame hay production averages (CEIC, 2023). Blanco-Canqui's (2022) data would suggest a carbon sequestration rate of 0.07 Mg C /ha/ year assuming annual additions of this scale. Green manures are commonly included in rotations on a one-in-two or one-in-three or one-in-four-year basis. With these less regular additions, the corresponding long-term carbon sequestration rates would be 0.035, 0.023 and 0.018 Mg C/ha/year, respectively. These are very low carbon sequestration rates. Actual carbon sequestration rates would be still lower as this method of estimation assumes that the biomass inputs are 2-6Mg in the cover crop compared to no residue returns in non-cover cropped treatments. In reality, average Canadian residue returns of wheat and grain corn are estimated to average 2 Mg/ha and 4.3 Mg/ha – suggesting much lower and potentially negative carbon sequestration rates from green manures based on this method of estimation.

A third line of evidence is a meta-analysis of manure application effects on SOC dynamics by Gross and Glaser (2021). They reported that "The application of farmyard-, cattle- and pig manure showed the highest SOC increases (50%, 32% and 41%, respectively), while green manure and straw showed only minor effects." On average, they reported green manures increased SOC by 17% or 5.1 Mg/ha among 52 treatment comparisons (note this is not an annualized rate). Among the 52 comparisons, all but two studies were performed in the tropics and subtropics, and both were short-term studies (five years). The first 5-year study was made in Quebec and has already been discussed (N'Dayegamiye & Tran, 2001a). The second temperate climate study was made in China. It compared wheat-legume-green manure with wheat-summer fallow (Zhang et al., 2019). In this study, two of three legume-green manures improved soil carbon over fallowing. Again, summer fallows have also been shown to result in soil carbon losses in Canada so this result is not surprising (VandenBygaart et al., 2003). Among the remaining studies, nearly half involve the concentration of biomass harvested from other fields, often at very high rates (e.g. 20-45 Mg/ha). Such studies do not measure the loss of biomass return in the fields or brush where biomass was removed and are not relevant to the green manure question we seek to answer. Excluding studies with more than 10 Mg/ha of biomass addition (in situ or ex situ), we still find many of the studies are not relevant to the conditions of our question – e.g. have a summer-fallow control, or annual external biomass additions that green manures could not provide. In summary, the meta-analysis evidence provided by Gross and Glaser et al., (2021) does not provide compelling evidence that green manures would increase soil carbon in the Canadian context.

Finally, one important experiment missing from these studies is the Rodale Trial in Pennsylvania (Littrell et al., 2021). They compared an organic legume-mix green manure rotation (corn–rye, oats–clover and rye, soybean–wheat, wheat–vetch) and conventional (corn–rye, corn–rye, soybean–rye) rotation over 36 years. Both treatments were cover cropped with rye. Carbon inputs between treatments were similar and both the systems had cover crops. However, in the conventional system the concentration of soil carbon dropped 16% from 18.6 to 15.7 g/kg in the top 30 cm. The legume-based organic system-maintained soil carbon. This is a surprising result considering that no external nutrients were added to the organic legume system, while nutrients were removed annually. The study did not report changes in bulk density, but assuming it remained constant and was 1.5 g/cm^2, this results in a change of 13 Mg/ha or 0.36 Mg/ha/year. Canada's equivalent experiment in Glenlea, Manitoba showed that when a one-in-four year green manure was relied on to meet nitrogen needs, yields collapsed to about one-fifth of the fertilized, weed-controlled control (Carkner et al., 2020). Unfortunately, the soil carbon levels from the Glenlea trials have not been published.

In sum, four medium to long-term legume green manure studies in Canada do not show significant increases in soil carbon. There is limited evidence (two experiments) that mixed legume green manures increase soil carbon by approximately 0.4 Mg C /ha/year (Hu et al., 2018; Littrell et al., 2021).

3.1.2 How much do legume green manures reduce fertilizer manufacturing emissions?

Legume green manures can fix atmospheric nitrogen. This nitrogen can (partially) supply the following crop's nitrogen needs, reducing the need for nitrogen application from other sources, including synthetic nitrogen. Synthetic nitrogen production in Canada contributes to 7.5 Mt of CO_2e per year – about 10% of Canada's agriculture-related emissions (Qualman & National Farmers Union, 2022). These emissions have been rising with increased nitrogen use – they were 4.8 Mt in 2005. They eclipse transport emissions for nitrogen fertilizers which contribute 0.2 Mt per year.

The degree to which green manures can offset reliance on synthetic emissions is a factor of (1) the nitrogen supplied by the green manure, and (2) the frequency at which a green manure is included in the crop rotation. For example, in a theoretical one-in-two-year legume green manure-wheat rotation, if the green manure supplies 100% of the wheat's nitrogen needs, synthetic fertilizer could be fully replaced – though the total production over this period would fall by 50%.

Several, Canadian reviews and experiments provide evidence of how much fertilizer legume green manures can replace. In a review, Thiessen Martens and Entz (2011) estimated that typical green manures would provide 63 to 75 kg/ha in the Brown soil zone and 125 to 150 kg /ha to Black soil zone of the Canadian Prairies. Another review reported that in 5 of 6 Canadian studies the upper range of the nitrogen (N) content in the green manure was below 100 kg/ha of N (usually ranges typically being around 50-90 kg/ha) (Cherr et al., 2006). Since this is the N content of the green manure, the N amount supplied to the following crop can be expected to be lower – suggesting the fertilizer replaced would be somewhat lower than 50-90 kg N/ha.

In long-term trials in Swift Current, once green manure nitrogen systems were optimized, and synthetic nitrogen rates were based on soil nitrate tests, green manures were able to replace 30% of the N needs of the subsequent crop and 16% of the N of the crop thereafter (Zentner et al., 2004). Meanwhile, N'Dayegamiwe and Tran (2001a) measured N-uptake and yield following green manures. They concluded that "green manure application in both years was capable of providing one-third to two-thirds of the N required for wheat maximum yield, depending on the species." Fertilizer replacement values (FRV) used in Manitoba and Saskatchewan were calculated from a single trial from 1999, from relay cover crops planted after a winter crop (Thiessen Martens et al., 2005). Alfalfa provided the highest FRV to oats at the Winnipeg site (51–62 kg N /ha), followed by chickling vetch (29–43 kg N/ha), lentil (23–39 kg N /ha), and red clover (24–26 kg N /ha). In a parallel experiment in Carman, FRVs could not be calculated due to the poor establishment of the legume crops. The yields provided by the legume crops are reported in an earlier study as 1.8, 1.2, 1.2 and 1.1 Mg DM/ha for red clover, alfalfa, chickling vetch and black lentil (Martens et al., 2001). In drier conditions, these results and replacement values are likely to hold – e.g. long-term green manure yields in Saskatchewan were reported as 0.8 to 1.5 Mg/ha (Biederbeck et al., 1998). However, in many parts of the country legume green manure yields are often 2 Mg /ha to 5 Mg /ha depending on the crop and region (Angers et al., 1999; N'Dayegamiye & Tran, 2001b; Thiessen Martens & Entz, 2011).

Overall, assuming crop demand of 100 kg N/ha for a typical cash crop, it seems plausible to assume that, in optimal conditions, green manures could provide 30-100% of crop demand. Synthetic N production emissions are estimated at 2.6 kg CO_2e/kg N (Qualman & National Farmers Union, 2022), which for this typical cash crop is 260 kg CO_2e/ha. A one-in-two year legume green manure would thus reduce synthetic fertilizer production (emissions) by 30-100% (the legume itself does not need nitrogen) or by 78-260 kg CO_2e/ha. It would also reduce agricultural productivity by about 50% as half the land would be taken out of production. Meanwhile, a one-in-three-year legume green manure rotation would reduce N fertilizer manufacturing emissions by 20-66% or by 52-172 kg CO_2/ha and reduce agricultural productivity by 33%. In this scenario, valuing carbon at $100 per tonne CO_2e, would offset production revenue losses by only $5 to $17 per ha or $2 to $7 per acre. Where, green manures fail to establish well, which is not uncommon, they should not be expected to supply N – adding risk and reducing resilience of agricultural systems. While legume green manuring provides marginal benefits in reducing synthetic fertilizer production emissions, these come at a significant cost to production.

3.1.3 Do legume green manures reduce soil N_2O emissions?

Canada's soil N_2O emissions have risen from 4.2 to 8.5 Mt CO_2e since 2005 (Qualman & National Farmers Union, 2022). This constitutes about 12% of net agricultural emissions. About 0.2-5% of synthetic nitrogen is lost as nitrous oxide (Liang et al., 2020b; Rochette et al., 2018). High precipitation and heavy soils favour the large losses. Most N_2O emissions occur under wet conditions, where oxygen becomes limited, and certain microbes begin using nitrate instead of oxygen for respiration (denitrification). Emissions can also occur during oxygen-rich conditions when ammonium (often from fertilizer) is used as an energy source for microbes (nitrification). In addition, losses occur after nitrogen is lost from the field (e.g. leached or volatilized) and later converted to N_2O. These indirect synthetic N losses are estimated to contribute an additional 2.3 Mt CO_2e per year.

The main driver of the increase in N_2O emissions is synthetic nitrogen fertilizer use, which has nearly doubled since 2005 (Qualman & National Farmers Union, 2022). The Government of Canada has set a target of reducing fertilizer nitrous oxide emissions by 30% by 2030. This raises the question – what role could legume green manures play in reducing soil N_2O emissions?

As noted by Ferrara et al. (2021), few studies quantified N_2O emissions from legume green manure crops. An ideal experimental design would quantify (1) any additional agricultural emissions caused by the green manure. Soil N_2O emissions are attributed to agriculture when they exceed background emissions (i.e. emissions when no nitrogen is added to the system). As demonstrated by Rochette and Janzen (2005), legume production emissions are only slightly higher than background emissions. However, since green manures are not harvested, but incorporated, their emissions are likely to be much higher than normal legume crops (Kandel et al., 2020). (2) Experiments should also capture additional emissions occurring in the spring following the green manure. A substantial portion of N_2O emissions in northern climates occur during the spring-thaw cycles when high moisture conditions (melting snow) are combined with fresh crop residue nitrogen (from the previous season) and freeze-thaw cycles cause cell-lysis, rapid decomposition, and plenty of substrates for a microbial feeding frenzy (Wagner-Riddle et al., 2017). Indeed, Canadian emissions estimates assume that 36% of soil N_2O emissions occur during the spring thaw period (Environment and Climate Change Canada, 2023). With their high nitrogen contents and low carbon contents, incorporated green manures are especially prone to emit N_2O under these conditions. (3) Experiments should capture emissions during the crop following the green manure and compare them to the same crop grown with synthetic fertilizer and no preceding green manure.

Two experiments meet most of these criteria. Nadeem et al, (2012) in Norway and Westphal et al. (2018) in Manitoba. Nadeem et al.'s (2012) experiment involved a grass-clover green manure with a no-nitrogen oat control both followed by barley. During the green manure production year, the green manure was mulched three times or cut twice (with hay removed) and mulched the third time. The three times mulched green manure production emissions were significantly (24%) higher than the emissions of the unfertilized oats control. When only the last cut of the green manure was mulched, emissions were higher, but the difference was not statistically significant. Barley was planted as the subsequent crop. The three-times mulch green manure contained 190 Kg N/ha and the barley following green-manure had significantly (49%) higher N_2O emissions than the barley supplied with synthetic N (80 kg/ha). When only the last cut of the green manure was mulched, only 62 kg/ha nitrogen supplied by the green manure and emissions from the green manure-supplied barley were still 23% higher, though not statistically significantly different. The authors concluded that the, "*use of GM may stimulate N_2O emissions in cereal production relative to moderate mineral fertilization in a heavy clay soil.*"

Westphal et al. (2018) compared emissions between organic alfalfa green manure and conventional soybeans, both followed by spring wheat, at the Manitoba Glenlea site. The alfalfa green manure had half the emissions of a zero-nitrogen conventional comparison in a normal year and double the emissions in a wet year. Both comparisons were not statistically significantly different. Averaged across two years, the green manure production had 60% higher emissions than soybeans but again was not statistically significantly different. These emissions included spring thaw emissions of the year following green manure production. While not separated out, these emissions were substantially higher for the green manure than for soybeans. Wheat was planted after the green manure. Wheat following green manure had 73% lower emissions in the normal year ($p<0.05$) and 47% lower emissions in the wet year ($p<0.05$). Across both years, green manure production and spring wheat cumulative emissions were 17% lower ($p<0.05$) for the organic system.

Other experiments provide further context. Alluvione et al. (2010) compared spring and summer soil N_2O emissions from synthetic fertilizer (urea) and a spring-incorporated legume green manure in Italy. They reported no statistically significant differences. Carter (2014) performed a similar experiment in Denmark, except, to optimize nitrogen use from the green manure (and thereby prevent large spring thaw emissions), they harvested the green manure, stored it over winter in a sealed environment (i.e. as silage) and harrowed or plowed it in the following spring. Despite these measures, emissions per unit N were higher (though not statistically significantly different) compared to the application of urea. Fungo et al. (2019) showed reduced emissions from a kind of green manure (ground-up dried leaves) compared to urea by approximately 20% in Kenya. Sarkodie-Addo (2003) reported emissions reductions of non-legume green manures (i.e. no synthetic fertilizer replacement value) over synthetic fertilizer. Ferrera et al. (2021) estimated N_2O losses from a legume green manure were low but had no synthetic fertilizer control. Johnson et al. (2012) compared cumulative emissions of conventional and organic corn-soy-wheat over alfalfa-alfalfa rotation and found similar rotation emissions between organic and conventional production. This study did note that emissions per unit yield (i.e. the emissions intensity) of the organic crops were much higher than conventional crops due to the difference in yield between the systems. For comparison, the average Manitoba Glenlea N_2O emissions reductions also become statistically insignificant when results were reported in terms of emissions intensity (Westphal et al., 2018). Baggs (2000) found that green manures did not increase emissions relative to bare ground, suggesting green manures may not enhance emissions. However, soil N levels were sufficiently high that the green manure did not improve the subsequent crop's performance. In such a situation, the green manure would not provide an N credit and its emission contribution would also be obscured. Chirinda et al., (2010) compared an organic rotation with green manure and a catch crop to a conventional rotation without a cover crop. However, measurements were not made during the green manure production year nor in the subsequent year. Thus, no conclusions can be drawn from this study.

Taken together, the experiment results, while sparse, suggest that replacing synthetic fertilizer with green manures does not provide large soil N_2O emissions reductions. Rather, the common results are either no difference or a small emissions reduction. This finding is roughly in line with Canada's National Inventory Report (NIR) methods which would treat green manures as crop residues and assign a 14% reduction in emissions to crop residues compared to synthetic fertilizers[4].

3.1.4 The net impact of legume green manures on emissions and crop production

In summary, pure legume green manures may not substantially increase carbon sequestration or generally reduce soil N_2O emissions. Widespread adoption of a one-in-three-year legume green manure rotation could reduce synthetic fertilizer manufacturing emissions by approximately 20-66% or by approximately 52-172 kg CO2/ha/year in a crop rotation where the subsequent crop needs 100 kg N per ha. At least half of this reduction would come from taking land out of food/feed production to produce green manure. Over the rotation, the fertilizer emissions reduction would be valued at less than $6 per acre at current carbon prices. Such a transition would also result in a 33% reduction in production.

3.2 Do organic amendments for nitrogen reduce emissions?

Organic amendments – particularly manure and compost – are key nitrogen sources in organic crop production. Meanwhile, synthetic nitrogen fertilizer use (production and application) contributes about 22 Mt CO_2e per year, or 31%, to Canada's agricultural

[4] Liang et al., (2020b) proposed that the crop residue coefficient for N application be 0.28 based on a global meta-analysis of synthetic and organic nitrogen N2O emissions factors calculated by Charles et al., (2017). This would result in calculating green manures emissions as 72% lower than synthetic fertilizers. This approach does not align with the above-listed experimental evidence. The difference between the evidence provided here and Charles et al., (2017)'s results likely stems from the fact that the nitrogen in non-leguminous crop residues which would dominate their analysis. Such crops would have much less readily mineralizable N. The NIR did not end up using the recommendation, as per Table A3.4 – 30 of the 2021 and 2023 NIR reports, the 0.28 factor for crop residues was substituted with a factor of 0.86 (i.e. a 14% reduction over synthetic N). This is the same factor used for other organic inputs including manure. As indicated in the annotations accompanying the Table, the coefficient was "modified based on expert consultation" (Environment and Climate Change Canada, 2021).

emissions. This raises the question – if synthetic fertilizers were replaced with organic fertilizers (i.e. manure and compost), would this reduce agricultural emissions?

Possible outcomes are illustrated in a recent meta-analysis of wheat, corn and rice systems. Fan et al., (2023) performed a global meta-analysis of emissions of synthetic fertilizer replacements (SFRs) in the form of various manure types and straw in wheat, corn and rice systems. They found SFRs increased yields by 2% and SOM (i.e. soil carbon) by an average of 24%. SFRs impacts on field emissions varied by crop. In wheat, N_2O emissions were statistically significantly lower with SFRs, and CH_4 emissions were lower (not statistically significant). In corn, N_2O emissions were higher (not significantly, and CH_4 emissions were lower). Overall net emissions per unit yield with SFRs were approximately 38% and 21% lower for corn and wheat, respectively.

While such results are promising, they should be interpreted with caution. The results included upstream fertilizer production emissions but did not include the upstream SFR emissions (e.g. manure production and transformation). They also face the carbon transfer and storage vs carbon sequestration problem discussed in Part 2. Thus, considering that the straw and manure would have been applied to agricultural land regardless (which is the case in Canada, see (Fan et al., 2019)), these soil carbon increases are only relevant at the field level, but not the landscape level of analysis.

Thus, to understand how manure and compost application affects emissions it is worth (1) comparing production and application emissions of manure/compost and synthetic fertilizer, (2) comparing whether composting increases total carbon retention in soils, and (3) identifying whether manure and compost application are increasing soil carbon and reducing synthetic fertilizer use at the landscape level.

Nitrogen production and application emissions

Production emissions for synthetic N fertilizer in Canada is estimated at 2.6 tonnes CO_2e per tonne of N (Qualman & National Farmers Union, 2022). Nordahl et al. (2023) estimated CH_4 and N_2O emissions from composting to be 0.079 kg CO2e/kg wet manure and 0.105 kg CO2e /kg, respectively (average of 40 samples globally). Together, this is 0.184 kg CO_2e / kg wet manure. Larney et al. (2006a) measured manure and compost characteristics of solid beef manure, the most common source of solid manure in Canada, in Alberta and Manitoba. Using their measurements (averages 34.9% dry matter in fresh manure, 39.8% dry matter loss and 15 kg N per tonne of dry tonne compost), we can calculate an emissions factor per unit of N (see Table 3). First, 0.184 kg CO_2e per kg wet manure is 0.527 kg CO_2e per kg dry manure (assuming 34.9% dry matter). Second, 0.527 kg CO_2e per kg dry manure is equal to 0.875 kg CO_2e per kg dry compost (assuming 39.8% dry matter lost). Third, 0.875 kg CO_2e per tonne dry compost is 63 kg CO_2e per kg N (assuming 14 kg N per tonne dry matter). For stockpiled manure, using measured values from Larney et al. (2006a), we end up with an emissions factor of 43 kg CO_2e per kg N (assuming the composting and stockpiling emissions are similar). This assumption is made as studies comparing the emissions of stockpiling and composting cattle manure show no consistent greenhouse gas emissions differences between composting and stockpiling (see Ahn et al. (2011), Mulbry and Ahn et al. (2014), Amon et al. (2001), Pattey et al. 2005, Bai et al., (2020) and DeRosa et al (2021)).

Table 6: Calculating emissions factors per unit nitrogen for composted and stockpiled manure using emissions factor of wet manure from Nordahl et al., (2023) and Canadian compost characteristics measured by Larney et al. (2006a).

	Unit	Composted manure	Stockpiled manure
Emissions per kg fresh manure	(kg CO_2e/kg wet manure)	0.18	0.18
Dry matter in fresh manure	(%)	35%	35%
Dry matter remaining after composting/stockpiling	(%)	60%	78%
Emissions per unit dry compost	(kg CO_2e/kg compost DM)	0.88	0.68
Final compost Nitrogen concentration	(%)	1.4%	1.6%
Emissions per unit nitrogen in compost	(kg CO_2e/Kg N)	63	43
Reported nitrogen lost	(%)	46%	23%

For dairy manures, liquid storage is usually the main source of emissions. Walling and Vaneekhaute (2020) summarized five studies reporting untreated stored manure. These varied from <0.01 to 0.33 kg CO_2e /Kg N/day with four of five studies being above 0.01 kg CO_2e /Kg N/day. Emissions vary considerably by time of year and storage type. Nevertheless, an approximate midpoint of 0.015 CO_2e /Kg N/day for 120 days of storage works out to 1.8 tonnes CO_2e per tonne N. This is 70% of the emissions of synthetic N fertilizer production.

Beyond nitrogen production, at the field application stage, Charles et al. (2017) performed a meta-analysis of field emissions from fertilizers and organic amendments. They concluded that the type of organic amendment strongly influenced emissions. High-risk organic amendments (e.g. slurry manures) performed worse (1.21% N2O-N losses per unit N applied +/- 0.14%) (or 5.0 tonnes CO_2e per tonne N) than synthetic fertilizers (0.57% +/- 0.3%) (or 2.4 tonnes CO_2e per tonne N). Medium-risk groups (e.g. solid manure) performed somewhat better (0.35% +/- 0.13%) (or 1.5 tonne CO_2e per tonne N)[5] and low-risk groups (e.g. composts) performed best (0.02 +/- 0.13%) (or 0.83 tonne CO_2e per tonne N).

Summing production and application emissions for composting, we can estimate that composting nitrogen emissions are ~63 + 0.83 =~63.8 tonnes CO_2 per tonne N. Stockpiled solid manure emissions are ~43 + 1.5 ~=44.5 tonnes CO_2 per tonne N. Liquid manure storage and application emissions ~1.8 + 5 ~= 6.8 tonnes CO_2 per tonne N. These are all similar or greater than synthetic fertilizer production and application emissions which are 2.6 + 2.4 = 5 tonnes CO_2 per tonne N). Direct application of solid manure (1.5 tonnes CO_2 per tonne N) appears to be the only nutrient source with lower emissions. This assumes all

[5] Calculated by converting the molecular mass of N to N2O by 44/28 and the GWP of N2O being 265x CO2.

livestock production emissions are allocated to the livestock products. These are very rough estimates and actual emissions can be expected to vary widely. Allocations of the emissions of other crop nutrients are not considered here since nitrogen is the most important nutrient provided by manure. However, even if some of the emissions are allocated to other nutrients, most organic nutrient sources (stockpiled or composted manure and potentially liquid manure) are similarly higher emitting nutrients than synthetic fertilizers.

Table 7: Estimates of emissions factors for production and application emissions of synthetic and organic nitrogen sources. See text for derivations.

Source of emissions	**Storage or production** (kg CO_2e/kg N)	**Application** (kg CO_2/kg N)	**Total** (kg CO_2e/kg N)
Synthetic N Fertilizer	2.6 (manufacturing)	~2.4	~5
Liquid manure	~1.8 (120 days storage)	~ 5	~ 6.8
Direct application of solid manure	0 (none)	~1.5	~1.5
Composting solid manure	~63 (composting emissions)	~0.83	~63.8
Stockpiling solid manure	~43 (stockpile emissions)	~1.5	~44.5

The line between livestock and cropping emissions is often hard to distinguish (Qualman & National Farmers Union, 2022). However, from a life cycle accounting perspective, when manure is recognized as a valued product, the manure should be treated as a co-product and some of the production emissions (e.g. enteric fermentation of the livestock) should also be allocated to the cropping system (FAO, 2016). This would further raise the production emissions of nitrogen in organic systems.

In general, if organic agriculture uses existing manure and does not change manure management practices, the impact on emissions is minimal – neither affecting manure application emissions nor fertilizer production emissions (See Figure 4B). If however, organic farming practices change how manure is stored (e.g. composting rather than spreading fresh, GHG emissions rise dramatically (See Figure 4C). Note that composting is a common practice on organic farms. An important reason for this is to kill weed seeds and pathogens in manure (Larney & Blackshaw, 2003).

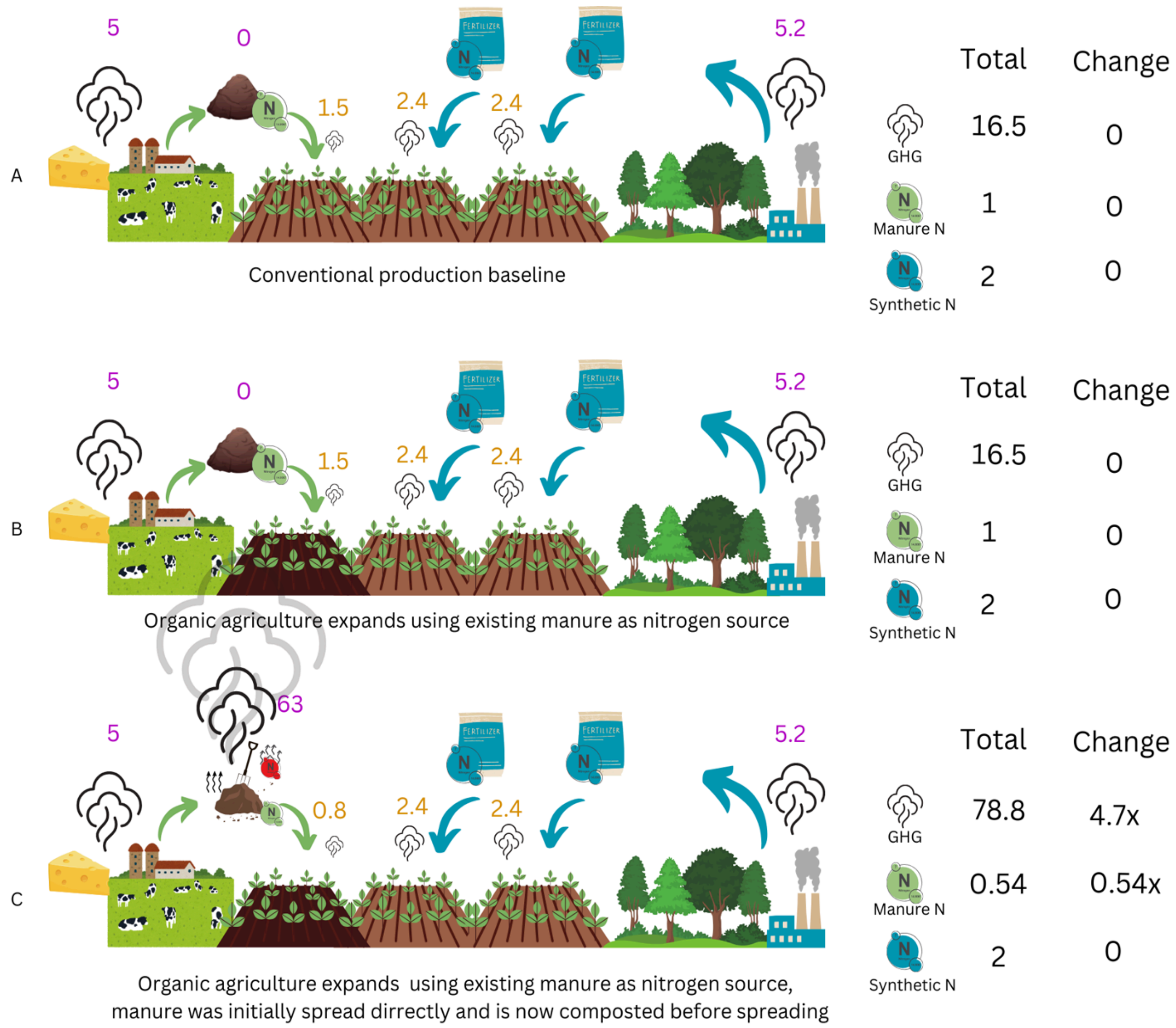

Figure 5: Nitrogen (N) related emissions (GHG) impacts of converting cropland to organic agriculture using existing manure as a nitrogen source without changing manure management (Scenario B) and with changing manure management from fresh application to composting (Scenario C). In the baseline scenario, emissions sources are from nitrogen production in the forms of an ammonia manufacturing plant and livestock. Emissions are calculated using the relative values in Table 4. Production emissions values are shown in purple and application emissions in orange. Livestock emissions (5 units) are not to scale. Emissions in Scenario C rise dramatically regardless of how livestock emissions are allocated.

Organic amendments and carbon retention in soil

Post-application, compost has a higher manure carbon retention rate (~36%) in soil than does solid manure (25%) or liquid manure (~5%) (Liang et al., 2021). This raises the question, does composting solid manure stabilize the manure so as to maximize soil carbon stocks? To answer this question, it is important to consider the losses of carbon that occur during the composting process. This carbon is lost as CO_2 and some CH_4 as microbes break down organic matter with and without oxygen. Larney et al. (2006b) estimated carbon losses from composting and stockpiling manure in Manitoba and Alberta. They reported average carbon losses during composting at 67% and from stockpiling at 38%. As a result, composting can be estimated to result in about 53% carbon losses compared to stockpiling and 67% carbon losses compared to no treatment (e.g. direct application). Thus, while composting has roughly 44% higher retention rates (~36% vs 25%) after application, the amount of carbon applied is about half to two-thirds less. Working these numbers out over 100 units of manure carbon, composting results in 12 units retained, stockpiling results in 16 units retained and not treating manure would result in 25 units retained as soil carbon. There is large uncertainty in all the figures used here. However, a reasonable conclusion is the gains in carbon retention for compost are offset by higher losses during the composting stage, resulting in no overall soil carbon advantage from composting.

Organic amendments from the farm to the landscape level

Finally, there is the question, does replacing synthetic fertilizer with manure reduce synthetic fertilizer use and increase manure carbon deposition? At the field level, the answer is 'yes'. However, at the landscape or national level it is less clear. At this level of analysis, manure availability for field application is determined by production (i.e. the livestock herd size and type). Since manure in Canada is already applied to soils, replacing synthetic fertilizer with manure locally does not affect the aggregate amount of manure applied or the subsequent soil carbon stocks. Local exceptions may apply when manure shifts from land with high manure application rates that is becoming carbon-saturated to a field with lower carbon or a heavier soil texture (Moinet et al., 2023). Considering that organic farms tend to show higher levels than comparable conventional farms, it is not clear that concentrating organic inputs on organic farms results in this optimal scenario.

Similarly, at the national level, replacing synthetic nitrogen with manure at the national level increases, by equal amounts, the land area not receiving manure and therefore requiring synthetic nitrogen to meet crop requirements. Exceptions here may apply when manure shifts from land where application rates exceed crop nitrogen removal to land to nitrogen is applied to meet crop demand. Thus, the overall benefit of replacing synthetic fertilizers with organic amendments of manure and compost in organic systems is a factor of the prevalence of these exceptions. And, if organic farms tend to be located on lighter, more workable soils and on soils with higher carbon stocks, it is possible that the opposite effect occurs (e.g. less optimal carbon transfer and storage). Excluding this carbon and transfer and storage problem, assuming that the frequency of cases of nitrogen application beyond crop removal is not significantly affected (over application of nitrogen in Canada is relatively uncommon (Lim et al., 2024)), and assuming the size of the national livestock populations is held constant, we can estimate that replacing synthetic fertilizers with organic amendments does not affect total manure-induced carbon in soils or aggregate synthetic nitrogen use.

In summary, synthetic fertilizer replacements offer advantages in terms of carbon retention in soils at the field level but not at the landscape level. When the transfer of carbon is considered, emissions factors for synthetic fertilizer replacements are not at all consistently lower than synthetic fertilizer. In typical Canadian manure systems (where liquid cattle manure is stored or solid manure is composted or stockpiled), the sum of storage and application emissions is greater than synthetic fertilizer nitrogen production and application emissions (per unit nitrogen supplied). Overall, if livestock numbers remain constant, increases in the adoption of organic nitrogen sources (i.e. manure and compost) would only redistribute emissions sources and carbon to Canadian soils, but would be unlikely to affect total emissions or carbon stocks.

3.3 Does tillage in organic systems contribute to emissions?

Organic farmers often rely on tillage for weed control since synthetic herbicides are not permitted. This tillage is often in the form of shallow secondary tillage which, as noted by Lynch (2011), is an important but still minor source of fossil fuel emissions. Recent evidence suggests the impact of tillage on emissions in Canada varies with climate and crop type.

Gains and losses of soil carbon in the Canadian context are often attributed to tillage. Canada's soils lost on average 24% SOM when native grasslands were first farmed (VandenBygaart et al., 2003). The cause of these losses is unlikely to have been tillage itself, but a reduction in carbon (C) inputs due to C removal through harvest. This is illustrated in a review of C dynamics after the conversion of grasslands to cropland by Mukumbuta and Hatano (2020). They found that SOC was strongly correlated with the net ecosystem carbon balance. No-tillage did not necessarily imply SOC losses. Indeed, they concluded occasional tillage could increase SOC in grasslands. Luo et al. (2010) performed a meta-analysis of paired no-tilled and intensively tilled plots and found that 'cultivation of natural soils for more than 5 years, on average, resulted in soil C loss of more than 20 Mg per ha, with no significant difference between no-tillage and intensive tillage. Increases were seen in the top layers in no-tillage, but not when the profile was measured to 40 cm. Further, Ogle et al., (2019) performed a global meta-analysis of SOC and no-tillage. They found that SOC did not statistically significantly increase in cool-arid environments. While no-tillage was associated with increased SOC under some conditions, they concluded that the uncertainties were large.

Liang et al. (2020a) summarized Canada's long-term no-tillage trials. In Eastern Canada, they found that no-tillage resulted in initial soil carbon declines and no statistically significant overall change in soil carbon in the long run. In Western Canada (Alberta and Saskatchewan), long-term no-tillage trials did show increased soil carbon in the top 15 cm. The increases are likely not due to the stratification of C in the topsoil as VandenBrygaart et al. (2011) report deeper resampling results in which SOC increases are still held. Sub-setting the long-term Western Canadian results gives an average of a 5.6% increase on trials over 15 years in duration (Liang et al., 2020a). For comparison, this is only 17% of what would be needed to attain a full reversal of carbon losses from conversion of grasslands to croplands. Interestingly, cumulative gains in the first 3-10 years were double those of the 20-year-plus duration trials. Apparently, gains in soil carbon in Western Canada are followed by losses which raises questions about the permanence of gains.

It is possible that the presence of soil carbon increases in Western Canada and the absence in Eastern Canada can be explained by changes in yield and carbon inputs in no-till systems. VandenBrygaart and Liang. (2024) quantified the changes in yield on no-till trials in Canada. In Eastern Canada, no-till plots showed 6% lower yields than tilled plots. However, in Western Canada, they showed 10%, 7% and 9% yield increases for wheat, canola, and legumes, respectively. VandenBrygaart and Liang have already correlated these results with the Liang et al. (2020a) no-tillage results for soil carbon and that the yield increase in Western Canada could be explained by reduced water losses from tillage.

Explaining changes in SOC in no-till plots in Western Canada's long-term trials as a matter of increased crop residue returns is further supported by crop-modelled estimates of annual SOC changes from residue return and no-tillage on a variety of crop rotations in Canada's semi-arid regions (He et al., 2021). The explanation also matches the classic understanding of SOC being a function of carbon inputs and decomposition rates (Coleman & Jenkinson, 1996).

No-tillage in areas of higher precipitation regions of Canada (e.g. Eastern Canada and BC's South Coast) is correlated with higher N_2O emissions (Pelster et al., 2024). Since most of Canada's organic horticulture production occurs in Ontario, Quebec and BC, the available evidence suggests the adoption of no-tillage in these systems would result in reduced yields, short-term losses in soil carbon, and no overall gains in soil carbon, and could increase N_2O emissions.

Finally, since tillage is an important tool in organic systems as a tool for weed management, emissions per ton produced could rise dramatically where avoiding tillage results in weed infestation. Where propane is used instead of tillage or herbicides, propane can add substantially to emissions (Bos et al., 2014). Similarly, tillage is a tool to incorporate manure. Failing to incorporate manure can increase emissions. Tillage is often especially important in horticultural settings where crops are grown on raised beds or require special soil preparation. The lack of tillage, for example in potato production, is often correlated with large yield declines (Djaman et al., 2022). Where large yield declines occur, soil carbon inputs fall and soil carbon may also fall.

In summary, higher tillage intensities in organic systems in Eastern Canada are likely not to result in additional GHG emissions – indeed, they are likely to reduce net emissions. In the Western Canadian prairies, tillage in organic cereal production may contribute to higher emissions.

3.4 Pesticides and emissions

Essential to organic production is the abandonment of synthetic pesticides. Pesticide use is generally not calculated as a major emissions source. For example, it is not directly included in NIR estimates or its adaptation for the agricultural sector (Environment and Climate Change Canada, 2023; Qualman & National Farmers Union, 2022). A study of the role of pesticides in agricultural emissions by Audsley et al. (2009) estimated pesticides contribute about 3% of GHG emissions of production of various crops in the UK. However, Audsley et al. (2009) did note contributions as low as 1% for corn silage and as high as 9% for certain potatoes (second earlies). More recently, in China, Yue et al. (2017) estimated 4-6% contributions for the carbon footprints of wheat, corn and rapeseed (e.g. canola), but much higher values for other crops, fruits and vegetables, such as 15%, 24%, 35%, 30% and 27% for soybeans, apples, citrus, open field cucumbers, and green peppers, respectively. Similarly, Cech (2022) estimated the contributions of pesticides to the emissions intensities of apples, viticulture, and sugar beets, reporting results of 51%, 37% and 12%. Cech (2022) did note that emissions factors for pesticide production are based on relatively old studies, and improvements may since have been made. Such high contributions to emissions from pesticides may explain some of the emissions differences for certain crops in Boschiero et al. (2023), especially for vegetable crops and apples. It also suggests that transitioning pesticide-intensive crops to organic production could reduce emissions per unit land area, and, if the organic yield gap is relatively small, per unit of food produced.

Summary of evidence and conclusions:

Answering the question, ‘Is organic farming better for the climate?’ is complex. The information available has improved dramatically during the last two decades. However, the answers are nuanced. In general, this report finds that emissions of organic crops are somewhat lower than conventional crops, though there is tremendous variability. Tripling the area of organic crop production in Canada would result in a slight (0.5-1%) reduction in total agricultural emissions and a slightly smaller reduction in total food production. Expanding organic agriculture (even to 25% of the land area) while maintaining total food production should not be expected to significantly reduce total emissions.

When external carbon sources are fully accounted for, soil carbon does not differ between organic and conventional agriculture indicating that organic agriculture does not affect carbon sequestration. Thus, while comparisons of organic and conventional farming show organic soils have higher soil carbon levels, this occurs at the expense of carbon elsewhere in the landscape. Since this is the case, total soil carbon stocks should not, in general, be expected to increase or be better maintained if organic agriculture is expanded. Any changes that do occur would likely be driven by changes in yield with reduced yields leading to declining soil carbon or by land use change with mixed green manures or higher perennial crop inclusion rates driving higher levels.

Using biologically fixed nitrogen from legume green manures reduces the carbon footprint of the subsequent crop but this occurs at the expense of a full season of production. Four long-term Canadian experiments have tested whether legume green manures increase soil carbon and found no changes. However, there is some evidence green manure legume mixes increase soil carbon (i.e. 0.4 Mg/ha/year).

Table 8: Summary of evidence

Component	Question	Type of evidence.	Finding	Overall impact of organic agriculture	Uncertainty
Organic agriculture in general	Does organic agriculture sequester more carbon into soils?	Three meta-analyses. 1 modeling study.	Two studies show no difference after accounting for external transfers of carbon (Alvarez, 2021a; Gattinger et al., 2012). One meta-analysis shows a positive difference, which can still be explained by external carbon transfers (García-Palacios et al., 2018). A modeling study shows reduced carbon inputs (mainly from lower yields due to lower nitrogen inputs) in organic production would negatively affects global carbon stocks by 9% (Gaudaré et al., 2023).	0 or (+/-)	Medium
	Are emissions lower for organic products?	80+ Life cycle analyses.	Results vary by study, but on average emissions per unit mass are ~15% lower. Emissions per unit area on average about 34% lower for organics. It is unclear where reduced emissions come from – reductions may be confounded by higher reduced N-surpluses in other countries and non-scalable effects of manure use.	++	Low-medium
	How does organic agriculture affect production?	Several Meta-analyses.	Results vary by crop, but in general ~25% reduction in yield (Alvarez, 2021b; Boschiero et al., 2023; de Ponti et al., 2012) ~20% reduction in harvested area (Alvarez, 2021b) This results in ~40% reduction in overall production.	--	

	Does expanding organic agriculture reduce emissions if total production is maintained?	This report, assuming current yield and emissions differences between organic and conventional production.	Maintaining overall production while expanding organic agriculture results in only minor changes in total emissions. If maintaining production involves expansion of agriculture, emissions increase.	~0/++	
Green manures	Do green manures reduce N_2O emissions?	Two full cycle experiments (measured GM production and following crop emissions), a few other related studies.	Producing green manures does not result in emissions reductions (Rochette & Janzen, 2005) N2O emissions in the following spring vary, but are generally comparable to using synthetic nitrogen emissions (Nadeem et al., 2012; Westphal et al., 2018).	0 (+/-)	Medium
	Do green manures reduce synthetic fertilizer production?	Fertilizer replacement studies summarized in two reviews.	Yes, a good legume stand can produce 33-100 kg/N per year (Cherr et al., 2006; N'Dayegamiye & Tran, 2001; Thiessen Martens & Entz, 2011) Thus, in a best-case scenario, a one-in-two year green manure can meet typical crop N demand.	++	Medium
	How much can green manures reduce synthetic nitrogen emissions?	Canadian emissions intensity of synthetic nitrogen. Emissions intensities of Canadian crops.	Green manures provide modest reductions in emissions of subsequent crop's emissions. Synthetic nitrogen manufacturing emits 2.6 kg CO_2e/ kg N (Qualman & National Farmers Union, 2022). This is 260 kg CO2/ha for 100kg/ha N (typical crop N demand). Emissions for most Canadian crops fall between	+	Medium

		Typical nitrogen rates in Canadian crops	1000 and 3000 kg/ha (Clearwater et al., 2016) thus, emissions fall by about 9-26% for typical crops.		
	Do green manures sequester carbon?		Several long-term legume green manure experiments in Canada show no in change in soil carbon (Biederbeck et al., 1998; Campbell et al., 1991a, 2001, 1991b; N'Dayegamiye & Tran, 2001) Two experiments show evidence that legume- mixes can increase soil carbon. (Chirinda et al., 2010; Hu et al., 2018; Littrell et al., 2021). 11/5/24 8:34:00 AM	0/+	Medium
	What is the net effect of green manures on emissions?		Modest to moderate reduction in emissions. High costs to production: (mostly) meeting nitrogen demands through biological fixation requires the previous crop be taken out of production. Possible carbon sequestration for mixed legume stands.	~0/+/-	Medium/ subjective
Organic amendments	Do organic amendments reduce emissions at the plot level compared to synthetic fertilizers?	Meta-analysis	Significant reductions in emissions. E.g. 38% reduction for corn and 28% for wheat (Fan et al., 2023)	++	Low
	Do organic amendments reduce emission at the landscape level?	This report	If organic amendments are already applied to soil, no additional benefits should be expected.	0	Medium

	Does composting reduce emissions?	A meta-analysis of compost emissions. A study of Canadian composting characteristics and losses.	Composting results in significant methane and nitrous oxide emissions (Nordahl et al., 2023). Based on typical characteristics of compost (Larney et al., 2006), per unit nitrogen composting emissions are very high (See Section 3.2, Table 3).	---	Medium
	Does composting increase carbon retention?	A meta-analysis of carbon retention studies. A study of Canadian composting characteristics and losses.	Manure carbon retention studies show higher carbon retention for compost compared to solid manure (Liang et al., 2021). Carbon losses from decomposition during composting are at least as high (Larney et al., 2006) and offset these gains. No overall net benefit.	0	High
No-tillage	What is the impact of-tillage in organic agriculture in Canada?	Two recent meta-analyses of Canadian long-term trials.	In Eastern Canada (higher rainfall): No impact on carbon (Liang et al., 2020). Risk of increased N_2O emissions (Pelster et al., 2024). In prairies, no-tillage results in reduced N2O emissions (Pelster et al., 2024), and increased soil carbon (Liang et al., 2020). Carbon gains may be due to yield gains from better moisture management (VandenBygaart & Liang, 2024) which may mean carbon gains may not occur in situations where yield gains do not occur.	+/-	Low-Medium

Manure and composted manure use at the local level can replace synthetic fertilizers. However, at the national level, their use is driven by livestock production and is likely to be unaffected by local replacements since manure is applied to soil in Canada regardless. In addition, the emissions associated with the use of common organic nitrogen amendments, (i.e. compost, stockpiled solid manure and liquid manure) exceed synthetic fertilizer production and application emissions.

By avoiding herbicide use, organic producers may rely more heavily on tillage. For Eastern Canada and high precipitation environments, this is unlikely to have negative emissions or soil carbon impacts. In Western Canadian cereal production, reduced or no-tillage can be expected to reduce emissions, especially if yields do not decline in no-tillage. Pesticides account for a substantial proportion (25-50%) of certain crops. Thus, reducing pesticide use may be a strategy for emissions reductions in some crops if yield declines are comparably smaller.

This report has considered available LCA data and the impacts of key organic practices on emissions. There are other practices typical of organic farming (e.g. increased use of shelterbelts) that have not been examined. Similarly, there may be characteristics of organic farming that have not been evaluated – e.g. increased nitrogen use efficiency.

On the whole, the available evidence indicates that the organic sector outperforms conventional farming in terms of emissions per unit area. Despite lower production, the sector also seems to outperform non-organic farming per unit mass of output. However, if total production is maintained, expanded organic agriculture (even by a large amount) is unlikely to affect agricultural emissions.

Growth in the organic sector is likely to result in positive outcomes for climate change mitigation if: (1) it involves replacing a large portion (e.g. 50% or more) of annual crops in a rotation with perennial crops or green manures. (2) It involves more efficient uses of manure – e.g. composting without nitrogen losses and emissions. (3) It involves sourcing manure from places where significant over-application is occurring and applying this manure to degraded soils or soils with a high carbon retention capacity (e.g. higher clay-content soils). (4) Organic foods are consumed as part of a low emissions diet – e.g. a low-meat diet. In this case, organic food is not a driver of reduced emissions; it is part of a diet that is. (5) The current yield differences between organic and conventional agriculture are reduced and/or emissions differences between organic and conventional agriculture are increased.

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Appendix 1: Adjustments to the Boschiero et al (2023) data set

Added data

A few relevant life cycle assessments were added to the Boschiero et al. (2023) dataset. This includes results of a study by Pelletier et al. (2008) on the impacts of organic production of Canadian canola, corn, soy, and wheat production. They reported a 32-34% reduction in emissions per unit mass for organic production of these crops. The LCA results of Seidel et al. (2017) from the Rodale trial in Pennsylvania, United States, were also added. We also disaggregated results to the crop level from Knudsen et al. (2014).

Data removed

In addition, several results were removed that had a large impact on the overall results and were not relevant. These were: (1) certain results of a study by Goossens et al. (2017). This study identified the emissions intensities of organic and conventional apples but also reported results for young and old apple trees. The emissions intensity of apples from young organic trees was 11x higher than that of young conventional trees. Both young and old tree results were excluded while the overall (full tree cycle) results were retained. (2) A Mediterranean climate study by Carranza-Gallego et al., (2018). This study compared old and modern wheat varieties under organic and conventional production over multiple years resulting in five outcome results – enough to substantially affect the overall wheat and cereal results. The organic and conventional sites were separated geographically which raised questions about the yield comparison. Manure use in the organic site resulted in negative carbon sequestration rates in some of the organic treatments. The transfer of carbon into the organic system does not affect overall manure carbon additions to soil and the emissions intensity difference is therefore not a scalable result (See Part 2 and Part 3 Section 3.2). This study was, therefore, removed from both the per-unit area and per-unit mass results. Doing so, brings the average emissions response for wheat in line with the Canadian LCA by Pelletier et al. (2008) study on wheat.

Handling outliers

Finally, five studies with a five-fold or large difference between organic and conventional production on a mass basis were considered as outliers and investigated. Two were due to mistakes. Boschiero et al. (2023) reported organic faba bean and yellow pea emissions results by Tidåker et al. (2021) as being about one-tenth of conventional emissions with conventional emissions being 1.8 kg per kg CO_2e. However, Tidåker et al. (2021) in fact reported conventional results of these crops as 0.18 kg per kg CO_2e. The organic conventional response ratio was corrected accordingly. In the three remaining studies, the ratio of organic to conventional emissions was different by a factor of 10 or more. These appear all to be due to external carbon transfers. Xu et al. (2020) and Huerta et al. (2012) accounted for carbon retention in soils from manure and compost in the organic system. This became the largest emissions category in the organic system. In Huerta et al. (2012), the overall carbon footprint of organic production became negative. Yoa et al. (2020), performed a simplified LCA in which manure and compost were used in organic vegetable systems and not in the conventional system. They did not specify whether carbon sequestration was the reason for the large difference in emissions. However, they did treat manure and composting as having no emissions. Considering that these studies' results can be explained by concentrated external carbon into the organic system which can be expected to have been applied to soils regardless, it was decided to remove them from the analysis. Again, see Part 2 for a discussion on organic agriculture and carbon sequestration.

After the above data adjustments, the per-unit area data showed one outlier - Temizyurek-Arslan and Karacetin (2022). This study showed high emissions in conventional production due to the excessive use of mineral fertilizer in the conventional production system in Turkey. Considering the difference is not driven by transferring carbon into the system, the study was retained.

Appendix 2: Methods for calculating crop emissions

Emissions estimates were calculated as the product of production amounts and the carbon intensities (CO_2e/kg produced). The conventional area of production for each crop was calculated using the Statistics Canada reported 2021-2023 seed area (or cultivated area) less the area of organic production reported by organic certifiers, compiled by the Canada Organic Trade Association (Government of Canada, 2024b, 2024a, 2024c). The conventional production amount per crop was calculated by multiplying this amount by Canada's 2021-2023 yield data (Government of Canada, 2024b, 2024a, 2024c). Organic production volumes were estimated as the product of the organic crop areas, the Statistics Canada yield data, and the relative changes in yield associated with organic production reported in Boschiero et al. (2023). All production estimates were transformed to a per-unit dry matter basis using per-crop dry matter data reported in a repository of crop LCAs (Poore, 2018; Poore & Nemecek, 2018).

Current conventional emissions were estimated as the product of total conventional production by crop and the Agriculture and Agri-Food Canada (AAFC) crop emissions factors reported by Clearwater et al. (2016). Current organic emissions were estimated as the product of total organic production, the AAFC crop emissions factors reported by Clearwater et al. (2016), and the relative change in emissions per crop reported by Boschiero et al. (2023). Clearwater et al. (2016) do not provide emissions intensity estimates for all crops. In such cases, the average of conventional LCA meta-analysis data from Poore & Nemecek (2018) was used after the data was filtered to Canada, the United States, and Europe.

Changes in emissions for a theoretical expansion of organic agriculture were calculated using the same calculations above but with increases in organic acreage (e.g. a three-fold increase) accompanied by the appropriate reduction in conventional acreage

Further explanations

Organic yield changes for pea, lentil, chickpea, flaxseed, canola, rye, spinach and blueberry were not individually reported in Boschiero et al. (2023). Thus, the general legume category was instead used for the legume crops. The average crop yield change (24% reduction in yield for organics) reported by Boschiero et al. (2023) was used for flaxseed, canola, rye, and spinach. No yield changes were assumed for the organic production of blueberries as reported in Montalba et al. (2019).

Spinach, blueberry, apple, and flaxseed dry matter contents were not reported in the Poore and Nemecek (2018) database. Instead, the respective dry matter values reported by Kunicki et al. (2010), Gonçalves (2015), Gebhardt and Thomas (2002), and Bozan and Temelli (2008) were used. Poore and Nemeck did not provide an emissions factor for conventional spinach. LCA data from Lin et al. (2024) was used instead.

Blueberry yields reported by Statistics Canada are very low if calculated as total production divided by the cultivated area. Instead, this yield data was adjusted to 15.8 Mg/ha based on data from British Columbia (Ministry of Agriculture and Food, 2017).

Finally, Boschiero et al. (2023) did not provide an emissions reduction factor for organic blueberries. Initially, an emissions reduction factor was extracted from Montalba et al. (2019). This study showed a 66% reduction in emissions for organics which significantly affected the overall results. However, Montalba et al. (2019) do not appear to have counted emissions of composting and did count emissions of synthetic fertilizer meaning their emissions reduction is likely highly overestimated. To avoid basing a large part of the overall analysis on this study, the average emissions reduction of Boschiero et al. (2023) was used instead.

2.3 Holos Case Studies

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December 2024

Executive Summary

Four case studies were modeled in Holos, a Canadian modeling software developed by Agriculture and Agri-Food Canada (AAFC) for on-farm greenhouse gas (GHG) emissions scenarios. The case studies are in the primary cropping regions of Canada and all have good organic data (Table ES 1). The conventional data, if not available from the site itself, was modeled using regional averages.

Table ES 1. Overview of the case study sites. Conventional rotations used conventional fertilizers to meet the crops' requirements.

Site	Type	First year organic	Years of data	Soil texture	Annual precipitation (mm)	Conventional rotation	Harvested crops	Organic amendments
Glenlea, MB	Replicated, phased research trial - 4 organic rotations	1992	2011-2023	Clay	542	Actual data (2 rotations)	Spring wheat, flax, oats, soybean, alfalfa	Green manures, composted cattle manure to meet P requirements
Moose Creek, SK	Organic farm - 2022 snapshot	1989	2022	Clay loam	455	Simulated (2 tillage levels)	Spring wheat, hemp, oats, flax, alfalfa seed	Green manures, manure used sparingly
Harrow, ON	Replicated, phased research trial - 3 organic rotations	2017	2018-2022	Sandy loam	801	Actual data (1 rotation)	Grain corn, soybean, winter wheat	Green manures
Victoriaville, QC	Replicated research trial - 9 organic rotations	2018	2019-2022	Sandy loam	896	Simulated (3 tillage levels)	Grain corn, soybean, winter wheat	Green manures and manure

How do the Holos outputs compare to published values? When compared on a rotation basis to the life cycle analysis (LCA) database in Boschiero et al. 2023, the emissions (direct plus indirect N_2O, farm energy and upstream) matched the LCA global warming potential values from respected long-term trials in the US and Europe. On an individual crop level the results were not as consistent with the global LCAs. Wheat, in particular, had a global LCA organic-conventional response ratio of 11% while the Canadian Holos results gave a comparison ratio of 92%. Some of the LCAs considered soil carbon (C) sequestration in their crop level comparisons, which Holos did not enable. LCA literature is not in agreement on whether soil C emissions/sequestration should be included in the global warming potential category, and if it is appropriate to present it by crop (e.g. Knudsen et al. 2014).

When Holos modeled N_2O emissions were compared to measured N_2O, rankings among the different rotations at Glenlea and Victoriaville were generally consistent. However, measured values at Glenlea, Harrow and Victoriaville were usually not within the Holos values' 40% uncertainty range.

Organic yields were 53-94% of conventional yields on a crop level, with the exception of soybean, which had slightly higher organic than conventional yields. When considering the whole rotation, organic yields could be as low as 33% of conventional due to lower crop level yields and the need for unharvested green manures in the rotation (Moose Creek). On the other hand, when organic rotations included alfalfa that was harvested for hay and compared to a standard conventional rotation, yields were higher (Glenlea). At the Eastern sites, whole-rotation yields of organic systems were 83 and 84% of conventional rotations as the rotations generally contain the same crops and do not take years out of cash crop production for green manuring.

How did emissions compare between organic and conventional rotations at each site? Table ES 2 shows that for representative rotations at each site, organic rotations had lower emissions except at Victoriaville, when expressed by kg of yield. In Holos, organic rotations generally had lower emissions from farm equipment and lower upstream emissions (from manufacturing of synthetic inputs). Differences in N_2O emissions depended on the site: at Glenlea and Victoriaville, N_2O emissions were equal for organic and conventional rotations, at Moose Creek they were lower for organic, and at Harrow they were higher.

Table ES 2. Comparing the organic and conventional rotation at each site that are the most representative of the crops and practices that farmers in the region use. Emissions presented here include: direct N_2O**, indirect** N_2O**, farm energy** CO_2**, and upstream emissions. O:C comparison ratio is the organic emissions divided by the conventional emissions in percent.**

	kg CO_2 eq per ha per yr			kg CO_2 eq per kg harvested yield		
Site	Organic	Conventional	O:C comparison ratio	Organic (O)	Conventional (C)	O:C comparison ratio
Glenlea, MB	494	748	66%	0.17	0.37	46%
Moose Creek, SK	264	925	29 %	0.29	0.34	85%
Harrow, ON	1,013	1,407	72%	0.17	0.19	86%
Victoriaville, QC	1,848	2,057	90%	0.47	0.43	107%

Each site was also compared on a crop level. Notably, in the Eastern systems the organic soybeans had higher emissions than the conventional ones (organic soybean emissions per hectare were 139-158% of conventional). This was attributed to soybeans' place in the organic rotations, where there was higher available N in the organic systems after the corn year, then lower available N in the cereal year, resulting in lower organic emissions (organic wheat emissions per hectare 54-72% of conventional). In other words, by looking at a single crop, the dynamics of the system were not being represented. Organic systems require the whole rotation to provide nutrients to each crop.

What about soil C? The soil C change output in Holos was not well calibrated in this modeling exercise, so it should be interpreted with caution. C inputs may be a better proxy for comparing soil C at a site; and the representative organic rotation selected at all sites except Moose Creek had higher C inputs than the conventional rotation.

Change in soil C was not available for Moose Creek due to the 1-year snapshot approach used for modeling at that site. Of the other three sites, Holos predicted that all the rotations at Harrow gained soil C while at the other sites, some rotations lost and other gained C. At Glenlea, one rotation performed very well for soil organic carbon (SOC) storage: annual organic plus alfalfa, which had five years of alfalfa. When SOC change was added to the other emissions, the Glenlea AO+A rotation – the only one with a forage crop in place longer than two years – was the only rotation that achieved net negative emissions (Table 1.6). At Victoriaville, the rotations that gained SOC also had higher N_2O emissions, but when the soil C storage in CO_2 equivalents was added to the other emissions, these rotations had lower emissions than the others at the site.

What did we learn about organic production? The Holos results showed that manure use in organic production is most helpful when used in moderation, like at Glenlea where it is used to meet crop P rather than N needs. Holos also showed high N losses for green manures, showing the potential for improving alignment of green manure termination and crop needs in the spring, as well as minimizing N_2O emissions. Finally, it was clear particularly from the Glenlea case study that adjusting management as time goes on is a key element for sustainable organic systems.

Recommendations for organic research include designing long term trials so that they are fully phased, using full rotations to compare organic to conventional rather than on a crop basis, taking soil tests to track SOC at regular intervals, and measuring N_2O emissions and SOC change on organic farms.

Recommendations for Holos modeling include, most importantly, calibrating the SOC levels as much as time and available information allow.

Recommendations for the Holos design team are included in the Conclusion and Recommendations section.

See the spreadsheet for complete results:
https://docs.google.com/spreadsheets/d/1c72ysG_zH_-I_kh7oFUCVSSkIFyDRSjD/edit?usp=sharing&ouid=111836906181919839880&rtpof=true&sd=true

This report provides interpretation and investigation into the results presented in the spreadsheet.

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Background

The Organic Task Force's goal is to summarize the research on differences in GHG emissions and co-benefits from organic vs non-organic farming systems in Canada. Upon doing a literature scan, it became obvious that for the major field crops in Canada, there was a lack of data comparing the two systems. Good data exists from model organic systems in key areas of the country, but in some cases there was no conventional comparison, and the field-level emissions data had not been brought together in an LCA-style summary of all emissions sources. To address this gap we used Holos, a Canadian model developed by Agriculture and Agri-Food Canada (AAFC) for on-farm GHG emissions scenarios, to model four case studies in key cropping regions.

The case studies were chosen where data was available and where the farming systems represented the largest cropping areas in Canada. When only organic data was available we modeled non-organic systems using regional yield averages and practices on the same fields.

Methodology

Case studies

Case studies were chosen in the two main cropping areas of Canada; the Prairies and Eastern Canada. The sites have excellent data from organic systems, and two are replicated trials that include conventional treatments. See Table 0.1 for an overview of the sites.

Table 0.1 Overview of the case study sites. Conventional rotations used conventional fertilizers to meet the crops' requirements.

Site	Type	First year organic	Years of data	Soil texture	Annual precipitation (mm)	Conventional rotation	Harvested crops	Organic amendments
Glenlea, MB	Replicated, phased research trial	1992	2011-2023	Clay	542	Actual data	Spring wheat, flax, oats, soybean, alfalfa	Green manures, composted cattle manure to meet P requirements
Moose Creek, SK	Organic farm	1990 ?	2022	Clay loam	455	Simulated	Spring wheat, hemp, oats, flax, alfalfa seed	Green manures, manure used sparingly
Harrow, ON	Replicated, phased research trial	2017	2018-2022	Sandy loam	801	Actual data	Grain corn, soybean, winter wheat	Green manures
Victoriavi	Replicated	2018	2019-202	Sand	896	Simulated	Grain corn,	Green

Ile, QC	research trial		2	y loam			soybean, winter wheat	manures and manure

Holos

Holos was chosen because it is Canadian specific, and although it is not LCA modeling software, it has similar outputs with a relatively user-friendly interface. It is a good alternative to using a spreadsheet to calculate emissions and suited the short timeline of the OTF project. Holos is designed for use by researchers, producers and policy makers. Because it is designed to compare different management options, it is ideal for comparison between systems at the same location – exactly what we hope to accomplish with the OTF project.

For the OTF case studies we used Holos version 4.0. All the algorithms in the model are listed in (Pogue et al., 2024).

Holos models farm level emissions (direct N_2O, indirect N_2O and farm energy CO_2), upstream emissions (from the manufacture of fertilizer and herbicides) and soil carbon changes. Holos uses location-specific historic daily weather dataset from NASA based on the longitude and latitude of the farm. The soil type is determined by the Soil Landscapes of Canada polygon, and Holos allows the user to select the best fitting soil type if there is more than one in a polygon.

The emissions categories that Holos generates are as follows:

- farm level emissions:
    - o direct N_2O estimates the field-level N_2O emissions from N applied, including fertilizer, crop residues and N mineralization.
    - o indirect N_2O are emissions that occurred away from the farm, by N03 leaching and runoff, NH3 volatilization, or biomass N that was transported away from the farm.
    - o farm energy CO_2 is the CO_2 from fuel use.
- upstream emissions from the manufacture of fertilizer and herbicides. There are no upstream emissions included for the production of other inputs such as manure or seed.

Holos gives the following uncertainty levels for the emissions it generates. These were used when comparing to measured values but are not presented when comparing among modeled values in this report.

- Direct N_2O 40%
- Indirect N_2O 60%
- Energy CO_2 40%

For the calculation of emissions per unit of yield, only harvested yields were included, i.e. anything that was plowed down, mowed, or left standing in the field as a fertility input was not included as yield.

If the case study in question included conventional plots in its design (as with Glenlea and Harrow), the rotations were modeled with the data available. For Victoriaville and Moose Creek, conventional comparisons were imposed on the same location using regional yield averages and representative practices. Decisions about the crops in the rotation, inputs and other management factors were made using resources such as provincial crop planning guides and consulting regional advisors.

The overall results of the Holos case study modeling can be found in the Excel document "Case study summaries". There is a tab for each case study and the third section in each tab, "Emissions tables" include the full summarized results of the modeling exercise for that location.

Soil Carbon

Holos also calculates an annual carbon balance including the annual change in carbon stocks in kg C/ha. We converted this value to CO_2 equivalent emissions or sequestration on an annual basis. These values are presented within each case study when enough data was available, but not in the high level summary tables.

We chose to use the Introductory Carbon Balance Model (ICBM) rather than the Holos default of IPCC Tier 2 emissions factors. This is a newer feature in Holos, intended to improve the reliability and flexibility of modeled soil carbon responses to management. ICBM is a two-pool model where young pool C decomposes faster than old pool C, and a portion of young pool C moves to the old pool based on a humification coefficient (Kröbel et al., 2016).

The carbon modeling strategy selected also affects the N_2O results. We ran informal sensitivity analyses between IPCC Tier 2 and ICBM and made the decision to use the newer model across the board. For most cash crops the IPCC estimate of N_2O was lower than when ICBM was used.

As a default, ICBM operates from a steady-state SOC starting point in 1985 for the management practices described and using Statistics Canada yields (Pogue et al. 2024; personal communication with Aaron MacPherson 2024). If climate, management practices and yields stay the same over time, the model stays at soil C equilibrium.

Rotation-level comparisons

An important use of the Holos case studies was to compare the emissions and economic performance of whole and representative rotations. Most LCA values are at a crop level, making it difficult to understand the full picture. Organic rotations can be quite different from conventional ones in the same region, because the system has different needs for fertility and pest management. Rotation differences are important features of organic systems that can impact the emissions, the yield, and the economic outcomes.

For the rotation–level analyses we have chosen the organic and conventional rotations that are most representative of the regional on-farm situation.

Paired comparisons

The comparison of emissions per unit of yield, on a crop level was used to compare Canadian values to global emissions reductions factors in a meta-analysis of LCAs that compare organic and conventional systems (Boschiero et al., 2023).

Because LCAs most often include upstream impacts in their models, upstream emissions were included in the emissions reduction factors (organic:conventional response ratios) that were calculated from the case study outputs. However, Holos does not include any upstream impacts from manure. Some authors believe that some of the upstream emissions from manure should be included in cropping system LCAs (Leip et al., 2019), but this methodology is not applied uniformly. Within the Boschiero et al. (2023) dataset there are studies that do not account for manure upstream emissions – for example, (Prechsl et al., 2017) and so the Holos results are reasonably well aligned.

If there are multiple rotations within a case study, we followed methodology from Boschiero et al. 2023 to achieve a pairwise comparison:

> “2.1. Data collection and analysis; 2.1.2. Type of cropping system: When a LCA case study considers different farming practices and only for some it was possible to perform a pairwise comparison between the organic and conventional system, the remaining practices were excluded. For example, in Perez-Neira et al. (2020) three cocoa cultivation systems are analysed: conventional monoculture, conventional agroforestry system, and organic agroforestry system. Therefore, in our analysis only the results of the conventional and organic agroforestry systems were included, excluding the conventional monoculture option, since the correspondent organic monoculture option is not included by authors.
>
> When a LCA case study presents more detailed technical management options (e.g. different options related to irrigation systems, intensity of pesticide treatments, cultivars) only for one of the two management systems, average impacts were derived for each management system to compare the results. This is the case for example of Avadí et al. (2020), that assess three pesticides treatment options (in terms of pesticide doses and application timing) under the conventional management of cotton production, while only one for organic production. Thus, in our analysis the average impacts of the three conventional options were compared with the impacts of the organic system.” Boschiero et al. 2023

Model Validation

Literature values were compared to the modeled results for each case study. N_2O measurements, when available, are compared to the Holos modeled direct N_2O results.

For soil C, data is largely insufficient to validate the model. Most sites do not report soil C change - and this data would be very helpful in understanding the functioning of these systems. There is also a challenge comparing measured soil CO_2 emissions to the carbon balance that Holos produces. Measured soil CO_2 emissions represent emissions from C decomposition (inputs and soil C pools). The modeled soil CO_2 is based on carbon stock change, so it encompasses both emissions and sequestration.

When LCA results were available, they were compared to the modeled results, as the categories of emissions are fairly aligned to the LCA methodology.

Modeled farm energy CO_2 was assessed to be reasonable (personal communication with Aaron Delaporte, 2024). The caveat was that in general, farm energy emissions were lower for organic systems than the conventional systems, presumably because of fewer passes for the application of synthetic inputs. However, organic systems do generally involve more light tillage passes for weed control, and these are likely not being considered by Holos.

Case Studies Introduction

Each case study is presented in emissions tables by crop and rotation. See accompanying spreadsheet for the tables in Excel.

The layout of each site's tables are as follows:

1. rotation comparison (comparing the two most representative rotations at the site)
2. paired comparisons (yield, emissions per hectare and per kg yield with upstream by crop and rotation; overall emissions including soil C change by rotation)
3. full summary tables for each rotation in 3 parts - 1) Rotation-level comparison, 2) per ha emissions, 3) a table with yield, C inputs and /kg emissions intensities.

These detailed, site-level tables are summarized for comparison among sites in section 1.

1. Summary Tables

See accompanying Excel document for all tables. Find these on the "Summary" tab.

Table 1.1. Rotation comparison summary - yield

Table 1.2. Rotation comparison summary - emissions per hectare

Table 1.3. Rotation comparison summary - emissions per kg of harvested yield

Table 1.1 describes the per hectare emissions for the four case study sites on a full-rotation basis. These are the comparisons of the two rotations that are the most representative of the farm systems in that region, at each site. For organic systems, looking at the whole rotation is more meaningful than crop-level comparisons because nutrient requirements are provided more on a rotation basis, rather than on a yearly basis, which is more common in conventional rotations. This table includes direct and indirect N_2O, farm energy, and upstream emissions from synthetic fertilizer manufacture.

The biggest contribution to the overall magnitude of emissions among sites is rainfall, as is evident in this table. Victoriaville, the highest rainfall site, has more than double the emissions of Moose Creek, the driest site.

It also *appears* that the difference between emissions from organic and conventional rotations is dependent on moisture; with the Victoriaville organic rotation having 90% of the conventional rotation's emissions and Moose Creek organic system at only 38% of the conventional emissions. Primarily, with higher rainfall comes higher direct and indirect N_2O emissions, they make up a larger proportion of the emissions and in all the case studies except Moose Creek, N_2O emissions are higher in the organic rotations. There may be an indirect effect that the lower moisture regions require more perennials or green manure years in the organic rotations to be sustainable, and that the rotations in the higher rainfall sites are more similar in composition.

Moose Creek is the only site where direct + indirect N_2O emissions are lower in the organic system (see results for the individual sites). This is likely the combined effect of 50% of the acres being in perennials, and the yields being lower in comparison to conventional than the other three sites (all research plots), there is overall less available N in the system.

Table 1.2 summarizes the emissions intensity, or emissions per kg of harvested yield for each site's rotation comparison. For all sites except Victoriaville the result is still lower emissions for the organic systems. At Victoriaville, with a small gap between the organic and conventional systems on a per hectare basis, and a slightly larger gap in yields (90% and 84% respectively), the emissions intensity for the organic system is slightly higher than the conventional system.

Table 1.4 . Rotation comparison summary - emissions per hectare, including soil C change

Table 1.5 . Rotation comparison summary - emissions per kg of harvested yield, including soil C change

Tables 1.4 and 1. 5 add emissions or sequestration from soil C change to the information presented in Tables 1.2 and 1.3 . This information is not available from Moose Creek with the modeling procedure of a one-year snapshot.

Of the rotations that were selected for comparison in the rotation summaries, the Holos model predicts that those at Glenlea and Victoriaville are losing C, and that those at Harrow are gaining C (see rotation comparisons at individual sites).

Glenlea and Harrow's comparisons become more favorable for organic when soil C is included, while Victoriaville's becomes more favorable for the conventional rotation. Zhou et al. (2017) found that with manure application instead of synthetic N in high rainfall, on sandy soils, N_2O emissions were higher (and higher than soil C sequestration), which may be what we see in the Victoriaville case.

Table 1.6. All rotations - N_2O and soil C change.

None of the selected representative rotations achieve net zero or negative emissions. Of all the rotations modeled (see Table 1.6 for all rotations at all sites), only one - annual organic plus alfalfa (AO+A) at Glenlea - was a net sequesterer of carbon according to the model. This rotation had 5 years of alfalfa plus 8 years of annuals (with the occasional green manure), so it had a lot of C inputs as well as being a Western and thus low-N_2O-emission site.

It's unclear if the C stock change in Holos was sufficiently calibrated even to compare among rotations at the same site. However, perhaps the clearest indicator of the potential for soil C change is comparing the C inputs at a site. When the representative rotations are compared at each site, all the organic rotations have higher C inputs except at Moose Creek.

Holos predicts that only at Harrow are all the rotations maintaining or gaining soil C. Yields and carbon inputs are high at this site, which has the longest and warmest growing season of the sites modeled (Climate Atlas of Canada 2019).

At Glenlea, the annual conventional rotation (AC), and perennial organic rotations, both with and without manure (PO+M and PO-M), are modeled to lose soil C over the 13 year period, while annual organic (with and without alfalfa), and perennial conventional rotations were gaining soil C over time.

At Victoriaville, only the corn-soy-cereal-cereal (CSCC) rotations were modeled to gain C, but for many reasons this result is not a good comparison to the other rotations. It likely shows up because the rotations are not fully phased and were only modeled for 4 years. In practice the rotation was: barley followed by winter wheat (2019) – winter wheat, then high yielding pea GM (2020 – a dry year that resulted in C loss for the other rotations) – grain corn underseeded to red clover (2021) – soybean (2022) (see Table 5.0.1). Any C losses related to the soybean crop, which contributes the least to soil C, may not have been captured because it occurred in the last year, whereas the other rotation types (CSC and CSCFF), soybean occurred earlier. For more discussion of the soil C results for Victoriaville, see section 5.3.

Comparing the N related emissions and C related emissions of the CSCC rotations is an interesting exercise: the CSCC rotations have higher N_2O *and* more C storage, resulting in lower overall emissions per ha and kg of product that all other Victoriaville rotations.

Table 1.7. Crop comparison summary - yield

Table 1.8. Crop comparison summary - per hectare

Table 1.9. Crop comparison summary - per kg of harvested yield

Tables 1.7 and 1.8 summarize the paired comparisons at a crop level. This method prioritizes direct comparison over what would truly be happening in the field and doesn't fully take into account the organic practices used. For example, a green manure crop may cause high emissions in the corn year, balanced by lower emissions in another year of the rotation. On the other hand, reduced yields on a rotation basis, for example if a cash crop year in a conventional system is replaced by a green manure year in an organic system, are not fully factored into a crop level comparison.

On a crop level, per hectare organic emissions (direct and indirect N2O, farm energy and upstream) are 36-84% of conventional emissions at Glenlea and Moose Creek.

In the Eastern sites, soybean always has higher per ha emissions in organic than conventional. This is largely because soybean has lower upstream emissions due to lower fertilizer needs, and partially because of soybean's place in the organic rotations, taking advantage of residual N after the corn year and therefore tends to have higher N2O emissions in the modeled outputs than conventional soy.

When looking at the emissions intensity on a per kg yield basis in Table 1.8, perennial organic wheat and flax at Glenlea are 28 and 42% higher than the conventional crops in the perennial systems, respectively. This flip is due to 45 and 41% lower yields in the organic crops respectively, a larger yield disparity than the wheat and oats.

At Victoriaville, the crop-level emissions intensities are overall worse for organic (Table 1.8). This is for the same reasons discussed above in the rotation level comparisons, namely that N2O makes up a larger proportion of the emissions in this higher rainfall site, and that there may be more emissions associated with manure than synthetic N, depending on soil texture (Rochette et al., 2018).

Table 1.10. Response ratios (organic to conventional) in (Boschiero et al., 2023) **and the Holos case study paired comparisons. Organic emissions are expressed in percent of the paired conventional emissions. LCA values are global warming potential, and Holos values are direct and indirect N_2O, farm energy and upstream emissions.**

Crop	**Response ratios** from GHG emissions in kg CO_2 /kg yield Mean (range and number of paired observations)	
	Boschiero et al. 2023 meta-analysis	**Holos case studies**
Wheat	11% (1%-161%, n=8)	92% (54%-130%, n=6)
Corn	86% (n=1)	94% (71%-108%, n=3)
Soybean	89% (59%-123%, n=3)	141% (137%-148%, n=3)
Crop rotation	87% (0.60%-1.48%, n=10)	85% (0.73%-1.05%, n=6)

Table 1.11. GHG emissions in kg CO_2 eq / kg yield in Boschiero et al. 2023 and the Holos case study paired comparisons. LCA values are global warming potential, and Holos values are direct and indirect N_2O, farm energy and upstream emissions.

Crop	GHG emissions in kg CO_2/kg yield Mean (range)			
	Boschiero et al. 2023 meta-analysis		Holos case studies	
	Organic	**Conventional**	**Organic**	**Conventional**
Wheat	0.21 (-0.004-1.25)	0.41 (0.09-0.79)	0.53 (0.15-0.93)	0.52 (0.25-0.86)
Corn	0.65	0.76	0.31 (0.12-0.4)	0.30 (0.17-0.37)
Soybean	0.82 (0.16-2.05)	0.73 (0.26-1.66)	0.49 (0.26-0.60)	0.35 (0.19-0.42)
Crop rotation	0.41 (0.003-1.13)	0.42 (0.003-0.99)	0.30 (0.16-0.44)	0.35 (0.19-0.49)

Table 1.10 and 1.11 compare the Holos pairs to the Boschiero et al. (2023) dataset that was used to build projections for the Organic Task Force project. The values for crop rotation (last row in each table) are comparable and within the same ranges for the emissions intensities (Table 1.11) and the response ratios (expressed in percentage in Table 1.10). The crop

rotations (n=10) in the Boschiero et al. (2023) dataset were primarily long term trials in Europe with comparable crops to the Canadian situation. It also includes the FSP long term trial in Maryland (Hoffman et al., 2018).

However, looking at the individual crops, organic crops are performing much better in global LCAs than in the Holos case studies. For wheat, this is largely due to the inclusion of soil C sequestration in some of the LCA studies resulting in net negative organic wheat emissions. In the Holos modeling, only one rotation out of the 23 modeled across all the case studies had net negative emissions. The Holos study could not accurately attribute soil C changes at the crop level however, so it is not included in Tables 1.10 and 1.11.

Soybean also has a higher organic-conventional response ratio in the Holos results than in the LCA results (Table 1.10).

2. Glenlea, MB

2.1 Description of site and rotations

The Glenlea long-term rotation was initiated in 1992 by Dr. Martin Entz at Glenlea, MB to test the question "can agricultural soils be as healthy as perennial grassland soils?" (Entz et al., 2024). It is Canada's oldest comparison of organic and conventional management. The rotations are described in Table 2.0.1. The Glenlea trial also includes a native prairie as a control treatment, but this was not handled well by Holos since it is not an agricultural system and is excluded from the OTF results presented here. Details of the Glenlea rotation study and the soil and environmental conditions of the area are provided by (Welsh et al., 2009) and (Bell et al., 2012).

The site is located 20 km south of Winnipeg, MB, in the Black soil zone, and the soil texture is clay. The annual mean precipitation is 542 mm. For more details of the site and treatments, see (Welsh et al., 2009), (Bell et al., 2012) and (Westphal et al., 2018).

Glenlea has each crop in each rotation represented within a year (i.e. it is a fully phased rotation trial). This is ideal because the effects of precipitation, residues and fertility have a substantial impact on N_2O emissions. Having each crop and rotation represented annually means that the effect of the year's moisture and temperature impact all the rotations equally, and the variation from the different rotations is more likely to show up.

Like most Prairie soils, the alkaline pH makes organic phosphorus management challenging. Rock phosphate has limited impact on available P. Low soil P leads to low forage yields which also limits N in the rotation. The perennial organic system, with forage exported as hay, was showing evidence of P depletion (Carkner et al., 2020). To manage the reduction in P, the plots were split in 2002 into PO+M and PO-M. Composted cattle manure was added to the PO+M plots in the first alfalfa year to meet the P needs of the crop.

The annual organic system also required a shift in management to remediate from encroaching weeds and N limitations. In 2015, the annual organic plots were split, with half seeded to alfalfa (AO+A rotation). The alfalfa crop was maintained for a full rotation before resuming the sequence. Therefore, in the emissions analysis that follows, the AO+A rotation cycle is considered to be a 13 year rotation.

Table 2.0.1. Glenlea long-term trial rotations that were entered into Holos for the years 2011-2023.

#	Rotation	Y1	Y2	Y3	Y4
		Crop			
1	Perennial Conventional (PC)	Wheat[a]	Flax	Alfalfa	Alfalfa
2	Perennial Organic +manure (PO+M)	Wheat	Flax	Alfalfa + manure	Alfalfa
3	Perennial Organic (PO-M)	Wheat	Flax	Alfalfa	Alfalfa
4	Annual Conventional (AC)	Wheat	Flax	Oat	Soybean
5	Annual Organic (AO)	Wheat	Flax	Oat	Hairy vetch/barley GMr[b]
6	Annual Organic + alfalfa (AO+A) [c]	Wheat	Flax	Oat	Alfalfa
	Prairie	Seeded grassland (since 1992)			

[a]all wheat is hard red spring wheat.
[b]green manure (GMr)
[c]in AO+A, Alfalfa was maintained for a full rotation (2015-2018), before resuming the AO sequence in 2019. AO+A is presented as a 13 year rotation in the emissions analysis.

2.2 Modeling methodology and sources

Holos modeling procedure

For the Glenlea modeling exercise, we had yield and management data for thirteen years, 2011-2023.

Conventional comparison

Because Glenlea has an organic and non-organic comparison in its replicated long term trial, there was no need for the OTF research team to develop a representative conventional rotation. This work was done by Dr. Entz's research team when they developed the long-term trial, using crops and practices that are used in the region.

Rotation-level comparison

For the economic analysis we selected perennial organic + manure (PO+M) for the organic rotation and annual convention (AC) for the conventional rotation. Westphal et al.'s 2018 study on N_2O emissions used these two rotations and gave the following explanation of why the organic rotation was chosen: "only the organically managed plots that received compost application were monitored *because they are more reflective of grower practice* [emphasis added] to supply phosphorus to soil."

Paired comparison

Following the methodology in Boschiero et al. 2023, we grouped the perennial and annual systems together for a pairwise comparison: PC vs avg(PO+M, PO-M) and AC vs AO. The perennial organic system has two management options: with manure and no manure. These were considered "more detailed technical management options" (Boschiero et al., 2023) and averaged for the pairwise comparison.

2.3 Results and Discussion

Emissions tables

Rotation-level comparison

Table 2.1 (spreadsheet). Glenlea rotation comparison.

Paired comparison

Table 2.2. Avg. emissions with upstream and change in soil C stocks, kg CO_2e per ha

Table 2.3. Avg. emissions with upstream and change in soil C stocks, kg CO_2e per unit of yield

Table 2.4. Avg. emissions with upstream, kg CO_2e per ha

Table 2.5. Avg. emissions with upstream, kg CO_2e per unit of yield

Table 2.6. Average harvested yield, kg/ha

Detailed emissions tables

Table 2.7 (spreadsheet). Glenlea rotation summaries

Table 2.8 (spreadsheet). Glenlea per hectare emissions

Table 2.9 (spreadsheet). Glenlea harvested yield, carbon input and per kg yield emissions

Model Validation

Before drawing any conclusions from the modeled systems, it is important to see if the Holos model predicted similar emissions as measured in the field. The Holos results are not consistent when compared to the measured values at Glenlea, but they are better when multiple years are factored in than a year to year comparison. This is likely due to the complex and differing dynamics at play with organic and synthetic amendments, as well as Holos' SOC starting point, which would have needed more time to fine-tune. As explained in (Braman et al., 2016), the relationship between microbial carbon and N losses may be an important factor, and may not be fully captured in Holos. Braman et al., 2016 found that the organic systems released less N_2O per unit of microbial biomass carbon than the conventional systems.

Nitrous oxide

Westphal et al. 2018 presents data on measured N_2O emissions from these rotations in 2014 and 2015. When averaged among two rotations (AC and PO+M) and three crops (wheat, soybean and 2nd year alfalfa) in 2014 emissions were 269 g N_2O-N/ha and in 2015 it was 923 g N_2O-N/ha (see Table 2, pg 47 of Westphal et al. 2018). From the Holos outputs, the same rotations and crops had modeled direct N_2O outputs of 1239 g N_2O/ha in 2014 and

1250 g N_2O/ha in 2015. See the converted values with uncertainty ranges in g N_2O compared in Table 2.10 below. There is little consistency between the measured and modeled values. The organic wheat in particular has modeled N_2O emissions that are much higher than the measured emissions.

Table 2.10. Comparing Holos outputs to field N_2O measurements in Westphal et al. 2018. Green highlight denotes values that are the same between the published and modeled values.

	Westphal et al. 2018, Table 2 g N20/ha	**Holos output - Direct N_2O emissions g N_2O/ha**	
	wheat, soybean and 2nd year alfalfa		
2014	423 ± 58a	1239 ± 496	
2015	1450 ± 149b	1250 ± 500	
2-year average	937	1245	
	2014 and 2015		**2011-2023**
Conventional wheat	1359 ± 161a	1381 ± 552	1274 ± 510
Organic wheat	594 ± 146b	2872 ± 1149	2374 ± 950
Conventional soybean	690 ± 128b	444 ± 178	417 ± 167
Organic 2nd year alfalfa	1104 ± 269b	282 ± 113	240 ± 96

letters indicate significant differences among groupings at $P < 0.05$

Braman et al. 2016 measured N_2O emissions from soil samples taken in the spring of 2011 from all six Glenlea rotations (Table 2.11). While the numbers are not comparable, because the sampling in Braman et al., 2016 does not cover the whole year, the emissions rankings can be compared (personal communication with Dr. Martin Entz, 2024).

Braman et al. 2016 found that the forage-grain (perennial) rotations had higher N_2O emissions than annual rotations, and that the organic plus carbon (PO+M and AO+A) had lower N_2O emissions than organic without manure (PO-M and AO) and conventional rotations (AC and PC). The authors attributed the higher N_2O emissions in forage-grain vs. annual grain rotations to the higher levels of available inorganic N in the former. When the 2011 Holos outputs are compared and the uncertainty of 40% factored in, it is obvious that the model is not sensitive enough to distinguish between these categories of systems.

If uncertainty is not considered, the organic + C in both the model and the measured value are the lowest (i.e. the rankings match).

For the annual vs perennial comparison, the rankings were opposite in 2011.

If more than just one year is considered, the Holos results are more aligned. This may be a more accurate way to make the comparison (and how Holos outputs are presented in this report), as the first year of ICBM – 2011 – is calculated differently than subsequent years. The direct N_2O average for all years and all three perennial systems is 953 g/ha and for all three annual systems, 880 g/ha. So throughout the time span modeled, Holos outputs are in agreement with published values (Braman et al. 2019) that there is more available inorganic N in the perennial rotations.

Table 2.11. Soil N_2O measurements in Braman et al. 2016 compared to Holos outputs for 2011. Ranking is in brackets.

	Braman et al. 2016, Table 1 N_2O (ng N g-1 h-1)	Holos output - Direct N_2O emissions 2011 g N_2O/ha	Holos output -Direct N_2O emissions 2011-2023
Annual rotations	1.11e-04b (2)	738 ± 295 (no difference)	880 ± 352 (no difference)
Perennial rotations	4.98e-04a (1)	668 ± 267 (no difference)	953 ± 381 (no difference)
Organic + C (AO+A and PO+M)	1.41e-04b (2)	602 ± 241 (no difference)	805 ± 322 (no difference)
Organic - C (AO and PO-M)	3.48e-04a (1)	649 ± 260 (no difference)	1013 ± 405 (no difference)
Conventional (AC and PC)	2.65e-04a (1)	858 ± 343 (no difference)	931 ± 373 (no difference)

letters indicate significant differences among groupings at $P < 0.05$

Soil C

Bell et al. (2012) measured SOC in 2008, after 18 years under four treatments: PO-M, PC, AO-A and AC, before the PO and AO treatments were split. They report SOC at 3 depths, of which 0-60 cm matches the depth used by Holos. At this depth, there was no difference among the four treatments and the average was 128,500 kg C/ha. Holos estimates the 2011 SOC at 0-60 cm to be 63,332 on average for the four rotations sampled in Bell et al. (2012).

In the published paper, at 0-30 cm and 0-120 cm, there were differences among the treatments: AO-A had significantly lower SOC than the other three treatments. However, upon discussion with Dr. Martin Entz, the values have since been adjusted using original soil samples taken in 1993, and due to a sandy subsoil below the perennial plots, the Glenlea research team now finds there is no difference among the four treatments after 18 years (personal communication with Dr. Martin Entz, 2024).

Discussion

The PO+M and AC comparison (Table 2.1) is really the most applicable, as it includes a well-functioning, adaptively managed organic system vs a standard conventional rotation. This is a unique feature of the Glenlea rotation in that it has been around long enough to require adjustments, compared to the other research sites in this report.

Adjusting management is an important point for the real-life situation of organic farms. Rotations need to be adapted to the evolving conditions such as fertility and weeds. This is a key support point for organic farms and the Glenlea site demonstrates that rotation adjustments are very important to maintain viability of the system. When comparing the adjusted to the unadjusted versions of the PO and AO rotations (PO+M vs PO-M and AO+A vs AO), the yields are at least half and the emissions intensities are between 50% and 400% higher in the unadjusted versions (Table 2.7).

In discussion with Dr. Martin Entz about this trial, he communicated that improvements continue to be made to the organic systems: in weed control and by using adapted varieties of wheat. In recent years the organic wheat yield in PO+M has been comparable to the AC wheat yield (personal communication with Dr. Martin Entz, 2024). In 2022 and 2023, the average yields for AC wheat is 2352 kg/ha and the PO+M is 2110 kg/ha; in 2011 and 2012 the yields were 2628 and 1323 kg/ha for AC and PO+M respectively, so the improvement is evident within the data available in this report.

The comparison between PO+M and AC shows higher organic per ha emissions for direct and indirect N_2O, and this is likely due to the previously mentioned higher available N in the perennial systems at Glenlea. When farm energy and upstream emissions are added, PO+M has lower emissions per ha. The per kg emissions of wheat are higher for PO+M, but as a whole system the emissions intensity is lower, because of alfalfa yields in PO+M being compared to annual crops in AC.

Of course, different methodologies for comparing these rotations yield different results. Using the Boschiero et al. (2023) method of paired comparison, with perennial and annual crops and systems compared (Tables 2.2-2.6), organic yields are overall lower. Per hectare emissions are still lower for organic overall. Per kg yield, the conventional perennial rotation has lower emissions than PO+M and PO-M (averaged) for everything except the two alfalfa years. This method of comparison does not take into account that organic systems require different crops and rotation design than conventional systems, which is perhaps a more direct, but less realistic comparison.

With the exception of AO+A, Holos seems to be estimating high N_2O emissions for the wheat crop when there is a GMr or forage plowed down. This is logical, but it would take more investigation to know for sure if this is the source of the variation for the wheat emissions. As evidenced in Westphal et al (2018), real emissions from a plowdown event depend dramatically on timing and soil moisture. Without the option of entering a plowdown date in Holos, it is difficult to know how it is considering the interactions between rainfall and the timing of available N in the system, but it is obviously not picking up on the complexities of this (see Table 2.10 for the much higher modeled than measured wheat emissions).

On a rotation level, when soil C stock change is factored in, the perennial rotations have an advantage for emissions per kg yield. The key to reducing emissions on a rotation basis, according to Holos and logically, is to leave a perennial in the ground for more than 2 years at a time, as in the AO+A rotation, where five year alfalfa stand was used to remediate for weeds. Holos predicts that this rotation is a net sequesterer of C.

3. Moose Creek, SK

3.1 Description of site and rotations

Moose Creek Organic Farm is about 250 km south-east of Regina. The site is in the thin black soil zone and the texture is clay loam. Annual precipitation is 455mm (Environment Canada Climate Normals data for Estevan, SK). The organic rotation modeled was the real-life situation on the farm in 2022. The rotation was represented in a single year by apportioning the total land base to the different elements of the rotation (Table 3.0.1). The conventional rotation was set up in Holos on the same site using the crops that occur in that region, divided proportionally on the land base.

Table 3.0.1. Moose Creek rotation descriptions.

Rotation	Crop	Portion of land base (ha)	Percent of land base	Description
Organic				
The organic rotation includes shelterbelt trees at 175 aspens per ha.				
Org	Wheat w manure	161.88	8%	
	Oats	104.01	5%	
	Flax	110.08	5%	
	Hemp w manure	112.1	5%	
	Green feed	58.68	3%	Oats and clover
	Oats w Alfalfa	50.59	2%	Oats underseeded to alfalfa
	Alfalfa seed	87.82	4%	Alfalfa harvested for seed
	Alfalfa	117.36	6%	Alfalfa – not harvested

	Fallow w Clover	524.89	25%	Clover plowed down in early summer, then left fallow.
	Fallow w Alfalfa	254.15	12%	Alfalfa plowed down in early summer, then left fallow.
	Fallow	129.5	6%	
	Wheat	333.47	16%	
	Hemp	31.16	2%	
	Total	***2075.69***	***100%***	
Conventional				
The conventional rotations include shelterbelt trees at 131 aspens per ha.				
Conv-NT	Wheat	768	37%	No-till
	Canola	892.55	43%	
	Flax	207.57	10%	
	Peas	207.57	10%	
	Total	**2075.69**	***100%***	
Conv-I	Wheat	768	37%	Intensive tillage
	Canola	892.55	43%	
	Flax	207.57	10%	
	Peas	207.57	10%	
	Total	***2075.69***	***100%***	

3.2 Modeling methodology and sources

Holos modeling procedure

Holos was used in “snapshot” or single year mode to model the farm and the conventional comparisons. Because of the one-year approach, soil C changes are not available from the ICBM model, which starts its calculation in the second year of a simulation in Holos. Therefore the data from Moose Creek includes direct and indirect N20, farm energy CO_2, and upstream emissions.

The shelterbelt component was used to include shelterbelt trees in both organic and conventional rotations. The density of trees in the organic rotation was based on research in the region showing that organic farms have approximately 20% of the land base in mixed perennial vegetation, of which approximately 35% is aspen trees (Xu, 2022). The tree density was taken from Su and Bork 2007. The organic rotation included both a shelterbelt with white pine and caragana, and unmanaged lands with poplar. The circumference of the trees was based on actual measurements from the farm.

Hemp residue coefficients were not included in Holos so they were generated based on Parvez et al. 2021.

Conventional comparison

The proportion of cash crops used in the conventional rotation was based on the seeded acres in SK Census Division 1 in 2017 from the Government of Saskatchewan (Gov of SK, no date). Average yields were based on both the 2017 regional census data (the best regional numbers available) and the SK Crop Planning Guide provincial average yields for the black soil zone (Government of SK, 2024). Fertilizer, herbicide and pesticide applications were based on the SK Crop Planning Guide’s black soil recommendations and verified and adjusted slightly for the thin black soil based on a regional agronomist’s opinion.

In order to understand how the model was responding to tillage level, the conventional rotation is presented with no-till and intensive tillage (all crops entered at the same tillage level).

Rotation-level comparison

The real-life organic rotation snapshot was compared to the no-till version of the conventional rotation, as no-till is the most common tillage level practiced in the region.

Paired comparison

The only two crops that are comparable between the systems are wheat (hard red spring wheat) and flax. Comparing on a crop level, when there were two “versions” of a crop, for example wheat with or without manure, the two emissions values were averaged and compared to the conventional crop’s emissions.

For conventional, no-till and intensive till were averaged for the paired comparison.

3.3 Results and Discussion

Emissions tables

Rotation-level comparison

Table 3.1 (spreadsheet). Moose Creek rotation comparison

Paired comparison

Table 3.2 (spreadsheet). Avg. total emissions with upstream (kg CO_2e per kg of yield)

Table 3.3 (spreadsheet). Average yield (kg/ha)

Detailed emissions tables

Table 3.4 (spreadsheet). Moose Creek rotation summaries

Table 3.5 (spreadsheet). Moose Creek per hectare emissions

Table 3.6 (spreadsheet). Moose Creek harvested yield, carbon input and per kg yield emissions

Model validation

Measured N_2O emissions from the thin black soil zone were not located. Without that information, Glenlea is the most similar site that has measured emissions.

Glenlea has measured direct N_2O emissions of 937 g N_2O/ha (two year average for wheat, soybean and 2nd year alfalfa; Table 2.10), compared to 818 g N_2O/ha modeled at Moose Creek (average of wheat, organic alfalfa and conventional pea).

Drilling down to a single crop to validate the model, the conventional wheat at Glenlea had 1359 kg/ha of measured N_2O but the organic wheat had only 594 kg/ha. Holos predicted much higher N_2O emissions for the organic than conventional wheat at Glenlea, but the rotation average had a more reasonable gap. At Moose Creek, the organic wheat had 554 kg N_2O/ha and the conventional wheat had 1531 kg N2o emissions/ha - quite consistent with the Glenlea measurements.

Organic alfalfa emissions were measured at Glenlea at 1104 kg N_2O/ha. In the Moose Creek model organic alfalfa had 775 kg N_2O/ha.

Moose Creek has lower annual precipitation than Glenlea. With only 1 year represented, the model is likely not accounting for any accumulated N in the system, and that may help explain the lower values.

Discussion

A sensitivity analysis was conducted without the shelterbelt components to understand the impact of including trees on the modeled outputs. Holos has a separate window for shelterbelt outputs and they do not affect the GHG emissions reported here, including indirect N_2O, which could conceivably be reduced in a real world situation by the inclusion of trees in the landscape. The shelterbelts also do not affect the field-level soil C estimates, which is logical as they are set up as a different component from the cropped fields.

Note that the soil C stock changes are not provided due to the method of modeling used (1 year snapshot using ICBM). However, Holos outputs include C inputs. C inputs in the organic system are 45% of the conventional system. This is related to yields as described below.

Yields and emissions are lower in the organic system compared to a representative no-till system: 33% of the yields and 38% of the farm level emissions per hectare on a full rotation basis. The low yields are due to half the farm's acreage being in green manure crops that are not harvested, as well as lower crop yields, with wheat being 61% and flax being 64% of conventional yields (Table 3.1). This demonstrates both the harvested yield sacrifices and the emissions reductions that can result from adaptive organic management.

Both crop and rotation-level yields are affected by low soil phosphorus (P) at Moose Creek (personal communication with Ian Cushon, 2024). In the Prairies, the alkaline soils are prone to low P and organic farmers lack tools to address it. Legumes, the primary source of nitrogen on these farms, require sufficient P, so a nitrogen deficit may also emerge from a low P situation. This is the dynamic leading to lower crop yields at Moose Creek. Innovative forms of P recycling, such as struvite, have been proposed as a solution for organic farms in the Prairies, but are as yet still not accepted by the Canadian Organic Standards.

The only area where the conventional system has lower emissions is when farm level emissions on a rotation basis are considered without upstream and on a per kg yield basis (i.e. direct and indirect N_2O plus farm energy CO_2). This is a direct reflection of the much lower yields in the whole system (33% of conventional yields; Table 3.1).

4. Harrow, ON

4.1 Description of site and rotations

The Harrow site and management is described in (Yang et al., 2023). The soil is sandy loam and it receives an average of 801 mm of precipitation annually. The fields were transitioned to organic from 2015 to 2017. The Harrow trial is fully phased, with each crop represented in each year. The conventional rotation is corn-soybean-winter wheat, a typical rotation for the area (although in practice, winter wheat is less often included - StatCan provincial averages from 2018-2022 show seeded area for wheat at half the area of grain corn and less than half the area of soybeans, Statistics Canada Table 32100359). In the organic rotations, green manures are used for fertility, and the trial compares red clover (frost seeded - RCfs and summer seeded - RCss), crimson clover and hairy vetch green manures. The frost seeded red clover was seeded in early spring (March or April) into the winter wheat crop, while the summer seeded cover crops (red clover, crimson clover and hairy vetch treatments) were seeded after the winter wheat harvest in July-August. Of these, summer seeded red clover and hairy vetch, and frost-seeded red clover were modeled in Holos.

Results from Yang et al. (2023) show that the crimson clover contributed the most biomass, followed by the RCfs, while the RCfs and the hairy vetch contributed the most biomass N/ha. The two cover crop treatments that contributed the most N led to the highest yielding corn crops. However, the RCfs competed with the winter wheat, reducing wheat yields compared to the summer seeded cover crops.

Table 4.0.1. Harrow rotations that were modeled in Holos using yield data from 2018-2022.

Rotation	**Abbrev.**	**Crop**		
		Y1	**Y2**	**Y3**
Organic				
Red clover - summer seeded	RCss	Corn	Soybean	Winter wheat, then RC green manure
Hairy vetch	HV	Corn	Soybean	Winter wheat, then HV green manure
Red clover - frost seeded	RCfs	Corn	Soybean	Winter wheat underseeded to RC

Conventional				
Conventional check	CK conv	Corn	Soybean	Winter wheat

4.2 Modeling methodology and sources

Holos modeling procedure

Five years of data were modeled from 2018-2022. Each crop and each rotation were represented in each year. As the moldboard plow was used in both organic and conventional systems, the “intensive” tillage option was selected in Holos. RCss and HV were modeled in Holos to compare the highest and lowest N contributions, and RCfs was used as the representative system.

Conventional comparison

The conventional comparison was implemented as part of the trial and so no conventional modeling exercise was undertaken.

Rotation-level comparison

For a whole rotation comparison, red clover frost seeded was selected as the organic rotation. Red clover is a more commonly used cover crop, due in part to its cheaper and more available seed. However, hairy vetch is a more suitable agronomic choice due to its high biomass N contribution without sacrifices to the winter wheat yield (Yang, 2024 personal communication).

Paired comparison

For the paired comparison, the two organic rotations modeled were averaged and compared to the conventional system.

4.3 Results and Discussion

Emissions tables

Rotation-level comparison

Table 4.1 (spreadsheet). Harrow rotation comparison

Paired comparison

Table 4.2. Avg. emissions with upstream and change in soil C kg CO_2e per ha

Table 4.3. Avg. emissions with upstream and change in soil C kg CO_2e per unit of yield

Table 4.4. Avg. emissions with upstream kg CO_2e per ha

Table 4.5. Avg. emissions with upstream kg CO_2e per unit of yield

Table 4.6. Average yield, kg/ha

Detailed emissions tables

Table 4.7 (spreadsheet). Harrow rotation summaries

Table 4.8 (spreadsheet). Harrow per hectare emissions

Table 4.9 (spreadsheet). Harrow harvested yield, carbon input and per kg yield emissions

Model Validation

Drury et al., 2021 measured soil N_2O emissions from an adjacent corn field on the same experimental farm for a three year period (2015-2017). The three year average with conventional tillage and no corn stover removal (which corresponds with the conditions in the modeled trial) is 2.79 kg N_2O-N/ha, or 4.38 kg N_2O/ha. The Holos output five year average for conventional corn was 2.33 kg N_2O/ha (40% uncertainty range = 1.398-3.262 kg N_2O/ha). The trial in question (Drury et al., 2021) was continuous corn, so it is not directly comparable, but the modeled emissions are lower than the measured amount even when the uncertainty is factored in. These modeled results should only be used to compare among treatments at the same site.

No measurement of soil C change is published from the trial to ground truth the modeled soil C outputs. A personal communication with Dr Yang (2025) indicates that these measurements were taken and a publication is upcoming. A summary of preliminary data suggests that the rotations with cover crops (i.e. the organic rotations) maintained or increased soil C since 2015 (Belanger and Yang, 2023). The Holos results do reflect this, with higher C inputs for the three cover crop rotations modeled and the organic rotations showing more soil C gain than the conventional one.

Discussion

The Harrow case study is particularly interesting because it does not import any manure, using winter green manures/cover crops for all the fertility needs of the organic system. The upstream emissions are therefore a more accurate comparison between the organic and conventional systems, as Holos does not assign any upstream emissions to imported manure when many sources believe that it should. In an LCA, there would be emissions assigned to the production and transportation of the green manure seed, but these are likely to be insignificant compared to upstream fertilizer emissions for the main crops (Viana et al., 2022).

Only five years post-transition, the Harrow organic system may still require adjustments. It would be very interesting to continue to follow this trial to see if fertility and weed control continue to function well.

Organic corn yields are 87% of the conventional yields while organic winter wheat yields are 64% of conventional (Table 4.1). This suggests that the N supplied by the green manure may be limiting by that point in the rotation. Organic soybean yields are slightly higher than conventional.

The conventional corn and soybeans have lower N_2O emissions than the corresponding organic crops (Table 4.1). By the wheat year, N_2O emissions are lower in the organic rotations. This reflects the comparative results for yield.

The organic soybean is higher yielding and has higher N_2O emissions than the conventional soybean. With low upstream emissions, organic soybean is the only crop that has higher emissions per hectare in all categories. Looking at the Holos outputs, the end of year N budget is much lower for the conventional soybean compared to all the organic rotations. The system requires more N at the end of the soybean year as there are no additional N inputs for the winter wheat, while the conventional wheat receives N fertilizer in the spring (110 kg N/ha).

The observation of different comparative results at different points in the rotation leads to an important point of comparison: organic systems require the services of a full rotation cycle to provide fertility and control weeds. To a lesser extent, this is true for all crop rotations, but in conventional rotations the fertility, pest and weed control are primarily provided within the year in question. This illustrates the importance of comparing on a rotation basis for organic systems.

All other organic crops and rotations have lower emissions on average than the conventional system, except for the farm-level (direct and indirect N_2O plus farm energy) per kg of yield. When upstream emissions are not included, the emissions intensity is higher in the organic rotation (Table 4.1).

The additional C from cover crops overrides the higher conventional yield biomass for all three organic systems, giving higher C inputs and more C stored on an annual basis. The stored C also overrides the higher N_2O emissions in the organic systems. When soil C flux is added to the total emissions in CO_2 equivalents, there is therefore a larger gap with the organic systems at 56% of the conventional for overall, rotation level emissions (Table 4.2).

The HV system is modeled to store more C than the other two organic systems (Table 4.8), but the C inputs were lower (Table 4.9). This output is confusing. The RCfs cover crop had an average yield of 19,567 kg/ha and the HV yielded 14,150 kg/ha (65% moisture). Looking at the starting SOC calculated by Holos, RCss was 98,830 kg C/ha, HV was 100,533 kg C/ha, RCfs was 107,251 kg C/ha and CK conv was 85,671 kg C/ha. These starting values, calculated based on the C inputs of the rotation back to 1985, may be indicative that the RCfs rotation is storing more carbon than HV over the longer term.

5. Victoriaville, QC

5.1 Description of site and rotations

The experiment is described in D’Amours et al. 2023 and the goal is to examine GHG emissions. The site is in Victoriaville, QC, the soil is a sandy loam, and it receives 896 mm of annual precipitation. It was transitioned to organic during 2016-2018. The trial has 15 organic treatments testing different combinations of tillage and fertility, is randomized and has four replicates, but is not fully phased. The main crops are corn, soybean and a cereal (barley or spring wheat). The trial also includes a permanent perennial forage treatment and a bare fallow, which were not modeled.

The trial is maintained by le Centre d’expertise et de transfert en agriculture biologique et de proximité (CETAB+), part of the Cégep de Victoriaville, QC. Ongoing information from the experiment can be found on CETAB+’s website (CETAB+, 2024).

Fertilization of the organic plots was determined by analyzing the GMr residues for N contribution and applying poultry manure to make up the remaining N requirement of the crop based on regional nutrient recommendations (D'Amours et al., 2023). Potassium sulfate was applied based on recommendations by crop.

Tillage was by moldboard plow (intensive) or by chisel plow (reduced).

Table 5.0.1. The Victoriaville rotations that were modeled in Holos and the conventional simulated rotations that were modeled at the same site. Both were modeled for 2019-2022. The organic rotations vary in length and are coded by the crops in the Rotation Abbreviation. Conventional rotations were modeled as fully phased, except when a crop did not appear in the organic rotation in that year, and then it was also omitted in the conventional rotation.

Abbreviation	**Tillage**	**Amendments**	**Crop and year**				
CETAB+ Organic rotations[a]:							
			2019	**2020**	**2021**	**2022**	***2023 (not modeled)***
CSC[b]-I-M	intensive	Poultry manure	Barley Pea GMr[c] manure	Grain corn RC[d] interseeded manure	Soybean	Wheat RC GMr manure	*Grain corn*
CSC-R-M	reduced	Poultry manure	Barley Pea GMr manure	Grain corn RC interseeded manure	Soybean	Wheat RC GMr manure	*Grain corn*
CSC-R-NM	reduced	no manure	Barley Pea GMr	Grain corn RC interseeded	Soybean	Wheat RC GMr	*Grain corn*
CSCFF[d]-I-M	intensive	Poultry manure	Grain corn RC GMr Manure	Soybean	Barley + forage undersown Manure	Forage	*Forage*
CSCFF-R-M	reduced	Poultry manure	Grain corn RC GMr Manure	Soybean	Barley + forage undersown Manure	Forage	*Forage*
CSCFF-R-NM	reduced	no manure	Grain corn RC GMr	Soybean	Barley + forage undersown	Forage	*Forage*
CSCC[e]-I-M	intensive	Poultry manure	Barley Winter wheat	Winter wheat Pea GMr	Grain corn RC interseeded	Soybean	*Cereal*

			Manure		Manure		
CSCC-R-M	reduced	Poultry manure	Barley Winter wheat Manure	Winter wheat Pea GMr	Grain corn RC interseeded Manure	Soybean	*Cereal*
CSCC-R-NM	reduced	no manure	Barley Winter wheat	Winter wheat Pea GMr	Grain corn RC interseeded	Soybean	*Cereal*
Conventional simulation:							
			Y1	**Y2**	**Y3**		
C-I	intensive	Synthetic fertilizer blend	Grain corn	Soybean	Wheat		
C-NT	no-till	Synthetic fertilizer blend	Grain corn	Soybean	Wheat		
C-R	reduced	Synthetic fertilizer blend	Grain corn	Soybean	Wheat		

[a]all organic treatments received potassium sulphate as needed

[b]CSC is Corn-Soybean-Cereal

[c]GMr = green manure

RC = red clover

[d]CSCFF is Corn-Soybean-Cereal-Forage-Forage

[e]CSCC is Corn-Soybean-Cereal-Cereal

5.2 Modeling methodology and sources

Holos modeling procedure

Experts at CETAB+ modeled nine organic rotations as described above with yield data from 2019-2022. Some treatments that are less likely to be used in real life were excluded. For the conventional comparison, a simulated rotation was modeled at the same site with different levels of tillage intensity.

To illustrate the difficulties with having crops not represented in each year at the CETAB+ trial, see Table 5.0.2. Looking at the conventional simulation, you can see how much lower the N_2O emissions are in 2020, which had a dry spring, with an annual total of 100 mm less precipitation than 2019 (D'Amours et al., 2023). Fortunately, corn and soybeans each have 3 years of data, of which one is 2020. For the cereals, wheat is only represented twice and so is barley. Therefore, for the comparisons, we will group wheat and barley together.

Looking at the yields of barley and undersown barley to see if it is appropriate to group them both with wheat, barley yield (only in 2019) is 1650 kg/ha and undersown barley (only in

2021) is 1937 kg/ha. Undersowing is an accepted organic practice and is therefore representative of an organic system. Therefore, in the CETAB+ rotations, "Wheat and Barley" includes numbers for wheat, barley and undersown barley.

To make the paired comparisons as direct as possible, conventional crops are omitted from the years in which they don't appear in the organic rotations. This means that conventional corn will be excluded for 2022 and soybean excluded in 2019.

Table 5.0.2. Holos-modeled direct nitrous oxide emissions (kg CO_2e) from CETAB+ data and the conventional simulation modeled in the same location. In the organic rotation, the combined Wheat and barley emissions are in yellow. In the conventional rotation, struck through figures are excluded from averages for the organic-conventional comparisons.

Crop	2019	2020	2021	2022	Average by crop
Organic – CETAB+ data					
Grain corn	1,641	689	4,590	-	**2,306**
Soybeans	-	329	1,606	2,354	**1,430**
Wheat	-	303	-	1,340	**821**
Barley	1,601	-	-	-	**1,601**
Undersown barley		-	1,441	-	**1,441**
Wheat and barley	1,601	303	1,441	1,340	**1,171**
Tame mixed (grass/legume)	-	-	-	209	**209**
Average by year	**1,614**	**440**	**2,546**	**1,301**	-
Conventional simulation					
Grain corn	2,774	647	2,911	~~2,865~~	**2,299**
Soybeans	~~936~~	223	1,099	1,040	**825**
Wheat	2,152	507	2,310	2,252	**1,805**
Average by year	**1,954**	**459**	**2,107**	**2,053**	-

Conventional comparison

The Victoriaville site is fully organic with no conventional comparison. In order to impose a conventional comparison with Holos, we modeled three conventional rotations (intensive, reduced and no-till) at the site in the same years. Unlike the organic data from the trial, in which each crop in the rotation is only represented in a single year, for the conventional comparison each crop was modeled in each year (2019-2022) by setting up three "fields" in Holos.

The composition of the rotation was determined with Statistics Canada seeded area data and consulting regional researchers. The goal was to model a grain farm with no livestock, and therefore no forages or silage corn are included. Provincially, from 2016-2023, soybeans and grain corn have about the same amount of acreage (approximately 375,000 ha), followed by wheat with nearly 1/4 of the area seeded (approximately 98,000 ha; Statistics Canada 2024). The modeled rotation was corn-soy-spring wheat, which means that wheat is over-represented at 33%.

Conventional yields were drawn from a nine-year average of regional Financière agricole du Québec data (FADQ).

Rotation-level comparison

For the rotation-level comparison the conventional and organic rotations that most represent the regional on-farm reality were chosen. For the organic rotation-level comparison the three year, intensive tillage rotation with manure was chosen (personal communication with Dr. Derek Lynch and Dr. Caroline Halde, 2024).

For the conventional comparison, we looked at StatCan data on tillage practices (StatCan Table 32-10-0367-01, Tillage and Seeding Practices, from the 2021 Census of Agriculture). Of 1.3 million hectares seeded in QC, 222,000 ha had no-till seeding, 612,160 ha had tillage retaining most crop residue on the surface, and 468,889 ha had tillage incorporating most crop residue into the soil. Unfortunately this data is not given by crop, but broadly, half of QC's seeded cropland uses tillage that retains most crop residues, but less than 20% uses no-till seeding. Therefore, the reduced tillage rotation was chosen as the most representative conventional rotation.

Paired comparison

For the pairwise comparison, two pairs were selected: intensive tillage and reduced tillage. For the organic reduced tillage, six rotations were averaged (three crop sequences x two amendment treatments). For the organic intensive tillage, three rotations were averaged (three crop sequences, all with manure). Conventional no-till was omitted as there was no corresponding organic option (as in Boschiero et al. 2023).

5.3 Results and Discussion

Emissions tables

Rotation-level comparison

Table 5.1 (spreadsheet). Victoriaville rotation comparison

Paired comparison

Table 5.2 (spreadsheet). Avg. emissions with upstream and change in soil C kg CO_2e per ha

Table 5.3. Avg. emissions with upstream and change in soil C kg CO_2e per unit of yield

Table 5.4. Avg. emissions with upstream, kg CO_2e per ha

Table 5.5. Avg. emissions with upstream, kg CO_2e per unit of yield

Table 5.6 (spreadsheet). Average yield (kg/ha)

Detailed emissions tables

Table 5.7 (spreadsheet). Victoriaville rotations summary

Table 5.8 (spreadsheet). Victoriaville per hectare emissions

Table 5.9 (spreadsheet). Victoriaville harvested yield, carbon input and per kg yield emissions

Table 5.10 (spreadsheet). Supplemental table: Conventional reduced tillage rotation by year and crop. Direct N_2O **kg** CO_2 **eq /ha**

Model Validation

Soil Type

Upon verifying the Holos modeled results with Joannie D'Amours, who carried out measurements at the site, it became apparent that the soil type in Holos was not quite accurate: in Holos it was a Eutric Brunisol with 77% sand and 10% clay, while the team at CETAB+ had classified it as a Humic Gleysol with 77% sand and 13.3% clay (personal communication with Joannie D'Amours, 2024). This may have some impact on the results but time was insufficient in the OTF timeline to adjust it.

Nitrous oxide, nitrate and ammonium

D'Amours et al. (2023) measured soil N intensity (NO3 and NH4) and N_2O emissions, combining these into CO_2 equivalents as global warming potential (GWP). This is approximately comparable to direct and indirect N_2O emissions from Holos; with the indirect emissions from Holos including emissions from residues removed from the farm, which is minimal but could make the modeled results higher. The comparable rotations are: MP-PMGM is T01 - CSC-I-M; CP-GM is T03 - CSC-R-NM; CP-PMGM is T02 - CSC-R-M.

The ranking between years appears to be consistent – 2019 has lower emissions for both modeled and measured values. Holos outputs are higher across the board than the measured values, even when considering uncertainty. Rankings among the systems are consistent between the measured and modeled values, with the no-manure system having the lowest N_2O and GWP.

Unfortunately we do not have a measured comparison for the CSCC rotations which showed very high N_2O emissions in Holos for corn in 2021. The CSC rotations that were presented in D'Amours et al. (2023) and shown in Table 8 had corn in 2020, which had a very dry spring.

Table 8. Comparison between measured data reported in D'Amours et al. 2023 and Holos modeling. For modeled GWP, direct and indirect N_2O are included with 40% and 60% uncertainty levels respectively.

		N_2O (kg N_2O/ha)		GWP (kg CO_2/ha)	
Rotation	Crop	Measured	Modeled	Measured	Modeled
		2019			

CSC-I-M (MP-PMGM)	Barley	2.72	5.27 ± 2.11	453	1,780 ± 781
CSC-R-NM (CP-GM)	Barley	0.82	3.67 ± 1.47	134	1,147 ± 488
CSC-R-M (CP-PMGM)	Barley	1.84	5.36 ± 2.14	299	1,726 ± 743
		2020			
CSC-I-M (MP-PMGM)	Grain corn	1.38	2.77 ± 1.11	217	1,184 ± 559
CSC-R-NM (CP-GM)	Grain corn	0.74	2.12 ± 0.85	109	686 ± 296
CSC-R-M (CP-PMGM)	Grain corn	1.23	2.67 ± 1.07	191	984 ± 444

Soil Carbon

A Masters thesis was completed on this site, measuring soil C and soil health indicators at the 0-5 cm depth (Corbeil, 2023). With a short time scale since the start of the trial (samples were taken in 2020 and 2021), it is unsurprising that there were no significant differences among the treatments for total soil C.

To validate the model, total SOC was compared to the Holos outputs. Averaging all SOC for the organic rotations in 2020 and 2021 from the Holos outputs gives a result of 174,552 kg C/ha. For the conventional rotations the SOC estimated by Holos (reduced and intensive till averaged for 2020 and 2021) is 79,464 kg C/ha. This is for a depth of 0-60cm (personal communication with Aaron MacPherson, 2024). The actual SOC at the site in 2019 was 85,000 kg C/ha according to soil tests taken by Joannie D'Amours (personal communication with Joannie D'Amours 2024).

It is evident from comparing the SOC predicted for the organic vs conventional rotations that the model uses the "current" rotation to generate the historic management, if none is given, and if no measured SOC value is entered. Since the organic rotations all have higher C inputs, the SOC was estimated to be higher. If both rotations had started at the same time from the same conditions, the organic systems would be storing more C than the conventional ones.

Comparison to LCA

Viana et al. (2022) conducted an LCA on one year of organic and conventional oats based on a farm in QC and found that N_2O emissions were between 1.08-2.26 kg N_2O/ha for organic and 1.87-2.29 kg N_2O/ha for conventional (comparison ratios for the two sets are 57% and 99%). The range is based on two sets of emission factors, with the higher values coming from Rochette et al. 2018 and the lower values from updated IPCC 2006. The overall average for cereal years modeled at Victoriaville is 4.6 kg N_2O/ha in the organic rotations and 6.6 kg N_2O/ha for the conventional rotations (comparison ratio 70%). These values are higher, but the ranking among organic and conventional is consistent and within the range identified by Viana and colleagues. The two sites are quite different, however, so the ranking is more important than the values.

The LCA found GWP per hectare of 1310 kg CO_2 eq/ha for organic and 1466 for conventional (89% comparison ratio). Holos modeling for Victoriaville resulted in 1768 kg CO_2eq/ha emissions for the organic cereals and 2714 for the conventional cereals (average of all rotations and years; Table 5.4; ratio of 65%). These results follow from the higher Holos estimates of N_2O. These figures do not include emissions from soil C change.

Discussion

As the highest precipitation site, N_2O values are highest at Victoriaville, and this impacts the compared rankings of organic and conventional rotations.

In all but one instance, the high yielding pea cover crop used at Victoriaville in the CSC and CSCC rotations generated higher modeled N_2O emissions than synthetic N. This green manure was terminated in the spring and followed by a corn crop in 2020 for CSC and in 2021 for CSCC. See Table 5.10 for N_2O emissions for individual years of conventional corn. Of these six instances of the pea green manure, only the CSC-NM rotation had lower direct N_2O emissions than the conventional corn.

The outputs clearly show that manured treatments have more direct and indirect N_2O emissions than the no-manure treatments. The increase of N_2O is from the manure itself and also from the additional biomass N associated with higher yields.

When considering farm level and upstream emissions for the representative rotations (Table 5.1), organic has marginally higher modeled emissions at the farm level (direct and indirect N_2O and farm energy), but when upstream is included, the organic rotation is marginally lower. The same thing shows up in per kg yield results.

Only soybean has higher emissions from the organic system once upstream emissions are included on a per hectare basis. This is because the upstream emissions for conventional soybean are quite low; minimal synthetic N is used. On average (Table 5.6), organic soybean yields were higher than the conventional soybean yields, which were based on regional averages for crop insurance.

At Victoriaville, manure was applied based on the N requirements after the contribution of the green manure was accounted for. As expected from the literature review conducted by the OTF team, this led to a smaller gap in per hectare emissions between the organic and conventional systems than if manure was not being used. Had the no-manure rotation (CSC-R-NM) been selected as the representative rotation (Table 5.1), the gap in per hectare emissions would be larger. For example, farm level plus upstream emissions for the whole organic rotation would be 66% of the conventional rotation, rather than 90%. Per kg emissions (farm level plus upstream) would also have a larger gap, and would have resulted in lower emissions per kg for the organic corn and the whole rotation (comparison to CSC-R-NM not shown).

Not having the trial fully phased at Victoriaville is a serious limitation to disentangling effects. See Table 5.8 (spreadsheet) that shows the effect of a dry spring in 2020 on the modeled emissions when all else is the same. The CSC rotations appear to have much lower emissions on an annual basis from the CSCC rotations (about half the emissions; Table 5.8). However, if these rotations were fully phased the result would likely be reversed. The corn emissions are very low in CSC only due to corn only occurring in 2020, which had a low moisture spring, resulting in low N_2O emissions. Another possible effect lower the CSC N_2O emissions is that the model did not consider the previous year's green manure. With corn represented 1 in 3 years in CSC you would expect to see higher average N_2O emissions than corn in 1 in 4 years (CSCC).

To confirm the effect of the green manure on the high CSCC N_2O emissions, an informal sensitivity analysis was conducted, removing the pea green manure, and then removing all green manures and cover crops from CSCC-R-NM. The N20 emissions (kg N_2O/ha) were as follows for the corn year: 16 kg N_2O/ha when all cover crops/green manures are included, 1.15 kg N_2O/ha when just the pea green manure was removed, and 0.93 kg N_2O/ha when all cover crops/green manures were excluded from the model. Therefore, the vast majority of the modeled direct and indirect N_2O emissions in that high-emitting system are from the high yielding, high N pea green manure.

Another limitation in this dataset is that the five-year rotations were not modeled fully because there were only four years of data available. Therefore, we only have 1 year of forages represented in the CSCFF rotations. Having two years of forages included would likely reduce the rotation level emissions of the CSCFF rotations, as the forage year has much lower emissions than all other years.

Analyzing three different tillage levels in the conventional simulation was revealing (see Tables 5.8 and 5.9): the only substantial difference was in the farm energy CO_2, where there are three levels of fuel use corresponding with tillage intensity. There was very little difference to the direct N_2O and no difference detected for the soil C stock change. The same pattern is evident in the organic rotations with the intensive and reduced tillage intensities, however, some yield differences occurred under the different tillage regimes. This is a reminder that having the same yields for the three conventional rotations doesn't capture the dynamics of the real world. However, it is useful as a sensitivity analysis.

Soil Carbon

Holos estimated much higher starting SOC for the organic rotations than the conventional ones (2019 average - 174,961 kg C/ha for all organic systems vs 79,339 kg C/ha for all conventional systems) due to the higher C inputs in those systems (Table 5.7). Therefore, the soil C change is not a clear representation of the differences between these systems if they had been implemented at the same time from a more recent baseline. Holos is assuming that the same management has been in place since 1985. As with all soil C assessments, the time scale is a significant factor and 4 years of data is probably insufficient to draw any conclusions.

All the caveats previously mentioned about comparing rotations when they have crops in different years apply here as well, as the N and C in Holos are modeled on the same basis for mineralization etc., within the ICBM (Pogue et al., 2024). Nonetheless, it is still interesting to investigate the model's outputs.

The CSCC rotations have the highest C inputs of the four sets of rotations (Table 5.9). Largely this is because soybean is only represented in 1 of 4 years, and there is a high yielding pea GMr that contributes a lot of C after the winter wheat. In an informal sensitivity analysis (results not presented), removing the pea GMr reduced the C input of the CSCC-R-NM system by more than half.

The overall result of the high biomass N and C inputs in the CSCC rotations are high N_2O emissions and high C inputs (C sequestration). According to the model, the N_2O tips the scales resulting in more emissions than sequestration in these rotations. This result is reflected in a global meta-analysis by Zhou et al. (2017), and they found this trend to be more prominent in climates and soils like that of the Victoriaville site; that is to say sandy loam with a tendency towards acidity and high rainfall.

However, the C sequestration does make the CSCC rotations lower in overall emissions than the other 3 sets of rotations (CSC, CSCFF and C). When C sequestration is taken into account, the CSCC-R-NM had the lowest overall emissions per hectare and per kg yield (Table 5.7).

Turning now to the highest emitting rotation set according to the model, CSCFF. Here we see the opposite relationship; low N_2O emissions and high soil C emissions. This system has the second highest C inputs, coming from the forage year. It also has soybean in 2020, the dry year, resulting in high soil C emissions from that year. When comparing to CSCC, the non-fully phased issue is even more apparent; with soybean in the last year of the CSCC rotations, Holos does not fully account for the probable soil C losses from that year.

The conventional rotations, with average yields that do not increase in the modeled years, are closest to steady-state systems, with relatively small modeled emissions from soil C stocks. Again, this is not truly representative of reality, where yields would differ year over year and among tillage regimes.

There are two comparisons in this case study where the non-fully phased issue should be less important; Table 5.1, 5.2 and 5.3.

When the rotations are averaged (Tables 5.2 and 5.3), which should largely resolve the non-fully phased issue, the organic rotations still have on average higher emissions from soil C changes. This is reflected in the rotation comparison soil C emissions where the crops and years are directly aligned (Table 5.1). The biggest difference is the low C input for the soybean year and the high input for the cereal year in the organic system - the fluctuations in soil C in the organic system are likely leading to higher modeled net emissions, as the model generates year on year changes primarily using the differences between the current and previous year’s C inputs.

However, looking at overall emissions in the rotation comparison (Table 5.1), the soil C emissions are not the primary factor. The organic rotation still has lower total emissions overall per ha, with lower N_2O emissions and upstream emissions than the conventional rotation. Per kg of harvested yield, the systems have essentially the same emissions.

Conclusion and Recommendations

Model Validation

Holos modeling with the ICBM did not align closely with measured emissions from the field. One contributing factor to this misalignment is likely that starting soil C values were not entered to create a common baseline for treatments at each site. The model therefore considers that the given rotation has been in place since 1985. In comparison to a modeled scenario in which a change in management occurred more recently, this changes the C dynamics (and probably also the N dynamics as they are interconnected), resulting in less C stock change as the model is closer to equilibrium.

At Victoriaville, modeled N_2O was double or triple the measured values, and at Harrow the modeled value was about half of measured values. However, comparing between sites, at Harrow the measured value for a conventional corn field was 4.38 kg N_2O/ha and the modeled value 2.33 kg N_2O/ha, and at Victoriaville the modeled value for conventional corn was 6.13 kg N_2O/ha. Compared to Harrow, it is logical that Victoriaville would have higher N_2O emissions, so the model seems to be more accurate in the latter case.

In the West, Glenlea's modeled N_2O emissions were 1.4x higher than the measured emissions. It is also important to understand that field measurements have different limitations (spatial variability for example) and cannot be considered perfectly accurate either. With an understanding of these caveats, the modeled values were not outside the range of possibility.

The exception was Moose Creek, where the N_2O values for the farm were much lower than published and modeled values. It is possible that the available N in the system is much lower and this is an accurate result, or it could be a limitation of the one-year modeling methodology used. On-farm N_2O sampling at established organic farms would be very interesting.

Modeled Outputs

When considering farm level and upstream emissions for the representative rotations, organic has marginally higher modeled emissions at the farm level, but when upstream is included, organic is marginally lower. The same thing shows up in per kg yield results.

This is partially why soybean has higher emissions intensity in organic than conventional: the upstream emissions for conventional soybean are quite low as minimal synthetic N is used. On average, organic soybean yields were higher than the conventional soybean yields at Harrow (research plot data) and Victoriaville (simulated conventional rotation using regional averages).

Another reason the organic soybean compares unfavorably to conventional soybean: its place in the rotation. The conventional crops' fertility is largely managed on an annual basis, with the application of synthetic fertilizers to meet the needs of the target yield. The organic rotations depend largely on perennials, green manures and cover crops that are contributing N usually less often than every year, so the dynamics throughout the rotation. This is illustrated in Harrow by different organic-conventional emissions gaps for the different crops in the rotation, with the wheat crop having a larger gap than the corn and soybean crops.

Across sites, high yielding green manures have higher modeled N_2O emissions than synthetic N. For example, at Harrow, red clover frost seeded has similar yields as the pea GMr at Victoriaville, and modeled N_2O emissions are higher in that rotation than in the no-cover crop conventional rotation (corn year; 1005 vs 627 kg CO_2 eq or 3.68 vs. 2.33 kg N_2O/ha). At Victoriaville, the difference is also about 1.5 x: corn in 2021 with a high yielding pea cover crop had 4550 kg CO_2 eq vs conventional 2985 kg CO_2 eq/ha (17 kg N_2O/ha vs. 11 kg N_2O/ha).

Manure also has an impact on N_2O emissions, especially in the high precipitation environment of Victoriaville. Using the no-manure rotation instead of the manure rotation in the rotation comparison reduces yields by 16% and N_2O emissions by 26%, leading to better emissions performance per kg yield without manure, when compared to the simulated conventional rotation. At Glenlea, where the manure in PO+M is used judiciously to meet P requirements, comparing to the no-manure rotation results in yields reduced by 46% and N_2O emissions decreased by 30%, suggesting that the benefit from the manure used at Glenlea is greater than at Victoriaville. Whether this is due more to the climate or the judicious application at Glenlea is difficult to parse.

It’s hard to tell how accurate the N_2O emissions factors (EFs) used in Holos are when considering organic vs synthetic fertilizers and variances in SOC under organic and conventional management. The data likely does not exist from the Canadian long term study dataset for systems that have low available N and high SOC - nor do we know for sure that these systems do result in higher SOC, when crop yields are lower.

Recommendations for organic

The following recommendations for organic production and research became evident during the analysis of the case studies:

On-farm:

- Judicious manure use may help to manage fertility while moderating emissions. The manure used at Glenlea to meet the forage crop’s P needs impacted yield more, and emissions less, than the manure used at Victoriaville to meet target N needs.
- Timing of tillage for terminating green manures, cover crops or perennials should be considered so that N losses are minimized in the spring thaw.
- Adjusting management as time goes on is a critical skill in organic systems - allow and plan for this to be needed, to make changes in response to yields and fertility.

Research:

- In organic trials, take regular soil tests to track SOC change.
- Trials should be fully phased.
- Use full rotation comparisons whenever possible for organic systems, rather than on a crop level.
- On-farm measurements of N_2O and SOC change would be excellent supporting information to characterize organic and low input systems.

Recommendations for Holos

Lessons learned

If possible, enter a starting SOC value for a field. The provision of more information to improve the C and N models allows a much better comparison among different scenarios. It may even be worth establishing an estimated baseline for a certain site so that Holos does not create a different starting point based on the management practices in each scenario.

If simulating a rotation, be aware that using average yields is not representative of real world situations, in that yields change year over year, and are different with different management practices. The yield averages used in these case studies could have been more finely tuned for a better comparison.

For the Holos developers to consider

Tillage in organic systems is likely insufficiently considered in Holos, and not well represented by the options of intensive, reduced and no-till. Generally, the farm energy is lower in the organic systems from Holos, presumably because there are more passes being considered from synthetic inputs. There may be more tillage passes in the organic systems for the purposes of weed management that are not considered by the model, since there is no option to enter the details of tillage (type of implement and frequency).

With the shelterbelt function in Holos available, it would be helpful if it could be integrated into the main emissions analysis to compare the C sequestration potential of differing acreage of uncropped and treed areas on a farm.

The carbon stock change calculation in the ICBM is confusing. Because it does not make a calculation in the first year, the soil C changes by crop are offset by one year, making it difficult to evaluate the soil C change associated with a given crop. This calculation differs from the IPCC Tier 2 model, in which the soil change from the biomass within a year shows up in that same year, rather than the next one. Further, it would require more work to understand clearly how the SOC starting points are being calculated, and they have a substantial effect on the SOC flux results.

It is clear from Westphal et al. (2018) that timing of incorporation of a perennial or cover crop is an important factor when there is a wet spring. An outstanding question is the discrepancy between the modeled and measured N2O emissions at Glenlea for 2014 (Table 2.10). Holos predicted much higher N2O emissions than were measured for wheat (averaged across the organic and conventional rotations). The organic wheat for 2014 and 2015 is also modeled by Holos to be much higher than the field measurements. It is possible that plowdown timing is being predicted in Holos, but could be better modeled if the date of plowdown was an entered value.

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Appendix 1 – Holos Questions and Answers

- **What is the depth that Holos uses to report soil C?** 0-60 cm
- **How much indirect N loss is from product removed from the farm? How is biomass exported determined (is it just residues, product, what about for forages)?** Biomass export is from crop residues and any manure transported off farm.
  - Note: I believe that “biomass export” would therefore include straw or harvested forages, not exported product such as grains.
- **ICBM: Unclear how it establishes the baseline steady state. Does it use your “current” practices to figure it out? Or does it use a reference value based on long term studies?** By default, Holos uses StatsCan small area data yields by year, going back to 1985. Using 1985 as the start year allows Holos to make a better estimate for starting soil C. More information is better: it is preferable to enter your own historical yields and/or the measured soil C values.
  - Note: still unclear what practices Holos uses to establish the baseline steady state. It would be important to ensure that if a change in practices has occurred (example: a change in tillage level), that this would be appropriately entered in the historic and current years. This was not done with these case studies.
- **EFs for N_2O… confirm if they are from Rochette et al. 2018 in both IPCC and ICBM.** Yes, based on this but more specifically: “described by equation 2.5.4-1 from Liang et. al. 2020.” in the algorithm document. Q: Does it take into account organic and synthetic EFs? A: yes.

2.4 Organic Field Crops Technical Report

By: Jackie Clark and initial work by Margaret Graves

Time was a limiting factor when constructing this report. Secondary and tertiary research questions are included in italics, indicating lines of inquiry that would and should be investigated, given more time.

Introduction

A growing demand exists for organic products, and in response to that, organic production in Canada has grown. In Statistics Canada's 2021 Census of Agriculture, the number of farms producing organic products had increased 31.9% since 2016. As of 2023, there are 5,965 certified organic farm operations spanning 3.18 million acres, according to the Canada Organic Trade Association's (COTA) production data, however this still makes up only 3% of the total number of farms and 2% of the total farm acreage in Canada (COTA, 2023).

There are tradeoffs between organic and conventional cropping systems. Organic farming eliminates the need for expensive synthetic inputs, and captures premium prices. Generally, growing crops and raising livestock organically provides lower yields, and therefore may require more land to produce the same amount of product. However, investments in research to improve organic yields could increase productivity while providing further economic and environmental benefits.

Investment in crop breeding for organic systems and improving nutrient and weed management are key to improving average organic yields. Canadian researchers are actively working on these goals. For example, the Organic Science Cluster program, representing an investment of $31.7 million in organic research over 15 years, addresses these among its national research priorities (link in).

This report focuses on organic field cropping systems. Canadian, North American and international literature was reviewed to assess our current understanding of the difference in ecological and economic impact between growing field crops organically and conventionally. In many cases, a lack of nationally-relevant data limits definitive conclusions for the Canadian context. Though relevant side-by-side conventional to organic field crop comparisons are limited, there is evidence to support the thesis that practices common to organic farming (e.g. reduced/no synthetic fertilizers or pesticides, green manures, diversified crop rotations) can improve environmental outcomes.

Organic field crops management and practices

What is an organic field crop system?

2018 data indicates that field crops and pasture/forages make up 35% and 62% of Canada's organic acres, respectively (COTA, 2018). There are two main types of organic field crop systems in Canada. First is the Canadian Prairies, a drier climate where dominant cash crops are wheat, oats, pulses, and oilseeds. Most of the farmland in Canada is found in this region and most of the organic acres are also found here. The Prairies receive around 400 mm/year in precipitation and as the soils developed under grassland, they are alkaline.

Second is the more humid southern Ontario and Quebec region, with higher rainfall (around 900 mm/year). The main field crops here are corn, soybean and winter wheat. This area has soils that developed under mixed woodlands and tend to be more acidic.

Table 1. Characteristics of the two major field crop systems in Canada. *2020 data from Organic Agriculture in the Prairies Report **2021 data from COTA via CountryGuide article

	Western Canada (primarily AB, SK & MB)	Eastern Canada (primarily ON & QC)
Climate	~400 mm/yr precipitation Shorter growing season, lower heat units	~900 mm/yr precipitation Longer growing season, higher heat units
Soil	Grassland origin, more alkaline, water conservation is important	Forest origin, moderate or low pH, higher moisture
Cash crops	Wheat, oats, pulses and oilseeds	Corn, soybeans, wheat
Organic production	26% of organic operations* 62% of organic acreage**	61% of organic operations* 26% of organic acreage**
Holos Case Studies	Glenlea, MB and Moose Creek Organic Farm (Cushon Farm), SK	CÉTAB+, QC and AAFC Harrow, ON
Practices of interest	Tillage and organic matter Green manuring, sources of phosphorus	Use of manure vs synthetic nitrogen vs green manure

What practices do organic systems use?

The Canadian Organic General Principles and Management Standards (CAN/CGSB 32.310) state that practices should promote soil health and fertility through increasing soil organic matter, balancing the supply of nutrients and stimulating biological activity (cite). Organic farmers can use ecological management practices and tools such as diverse crop rotations, including N-fixing legumes, and incorporating plant and animal matter such as compost, manure, green manure, cover crops, or other crop residue into the soil. These standards outline general prohibitions as well, including the prohibition of genetic engineering and nanotechnology.

The Organic Permitted Substances List (CAN/CGSB-32.311) clearly outlines substances that are permitted for use in organic crop production including soil fertility amendments, pesticides, storage aids, and processing aids (cite). Synthetic fertilizers and pesticides are prohibited in organic production.

Without the use of synthetic crop fertility and protection products, Canadian organic farmers employ diverse tools to optimize their yields. In general, organic farmers develop their cropping systems and in-crop practices to establish a competitive, healthy, and pest resistant crop. Soil fertility should be maintained through crop rotation, leguminous green manure crops, soil-building forage crops, supplementation with recycled nutrients from plant or animal origin (e.g. manure, compost, feather meal, crab meal), and use of raw mineral nutrients. Pest management includes practices such as pest resistant cultivar selection, increasing stand competitiveness with higher seeding rates, managing timing of crop seeding to offset pest pressure, and crop rotation and diversity to break pest cycles or support beneficial predators. Crop rotation is a very important practice for breaking weed and pest cycles in organic systems (Viana et al., 2022). Biocontrols may be used to support insect and disease management. Under the Canadian Organic Standards, farmers can use acetic acid for weed control, and plant extracts for pest control, however this is logistically challenging and cost prohibitive on the large acreages (Snyder and Spaner, 2010).

Other characteristics

Statistics Canada's census of agriculture and COTA data report on the number of organic operations, breakdowns by sector, and specific production data, however not much is publicly reported or easily available about other characteristics of organic farms. We have general data on the education, age, race, gender and other demographic and cultural factors for the general farming population. It would be beneficial to understand the intersectionality of identities of folk engaged in organic farming specifically, to better address specific opportunities or challenges these farmers encounter.

In *The World of Organic Agriculture: Statistics and Emerging Trends 2018*, Loftsgard and Guerra report that organic farmers in Canada tend to be younger than conventional growers, with 14.6 % of operators on organic farms under the age of 35 (compared to 9.1% of conventional operators). Organic farmers are also more likely to come from a non-farming background and be more highly educated (Loftsgard and Guerra, 2018). This might suggest the benefit of education (critical thinking, investigative skills, up-to-date innovations) for improved production, however also the challenge of lacking generational wealth and capital investments critical for large-scale agricultural operations, generational access to land, and established institutional knowledge and community vital to success in the industry.

Cranfield et al. (2010) found that health and environmental concerns were the most significant factors encouraging conversion to organic farming in Canada. In a review of existing data about organic farming in Canada, Lynch (2022) concludes by reporting that "demographic trends and surveys of perspectives of new entrants to Canadian organic farming are documenting an increasingly socio-ecologically complex Canadian organic farming sector."

Transition

Organic farms must undergo a 3-year transition period from conventional. The transition period has specific characteristics that are different from an established organic farm. It is a time when producers and their land are adjusting to new practices and yields can be lower as the system gets established. In the transition stage, the producer does not have the benefit of established ecological processes to moderate the system nor the chemical tools to control pests. The major constraint, however, is that the organic price premium isn't available during transition.

Venkat (2012) conducted a Life Cycle Analysis (LCA) of 12 crops grown in California, comparing conventional growing methods to an established organic system and transitional organic system. Horticultural crops, alfalfa for hay, and perennial nuts were evaluated, and emissions differences between management types varied widely by crop. On average, steady-state organic production had higher emissions per kg production than conventional. However, transitional organic production had 17.7% lower emissions on average than steady-state organic or conventional production - attributed to soil carbon sequestration during the transition period. Though not field-crop focused, this demonstrates a difference between side-by-side comparisons of conventional and organic systems, and stepwise evaluations of a transition to organic production.

Cooper et al (2011) conducted an LCA comparing conventional and organic scenarios on dairy farms in the United Kingdom, looking at both stocked and stockless treatments. Using data from the Nafferton Factorial Systems Comparison experiments, the crop yields represented organic production during transition. Excluding livestock from the scenario, baseline organic emissions were calculated to be 841 kg CO_2/ha, compared to 2019 kg CO_2/ha. However, crop yields were lower in the organic scenario, on average producing 22.4 GJ/ha of human food energy in the stockless organic scenario compared to 47GJ/ha in stockless conventional. This equates to around 36 kg CO_2/GJ in stockless organic and 43 kg CO_2/GJ - which are relatively similar. Researchers did not provide statistical analysis of emissions on an energy output basis. All organic scenarios, including those with livestock, produced lower yields - conventional scenarios led to greater crop production but also greater emissions.

A case study in Kentucky investigated energy efficiency and GHG emissions during transition to organic production, and found that emissions decreased (Clark, Khoshnevisan and Sefeedpari, 2016). However, this specific farm integrated many types of livestock with both field and horticultural crop production, and so changes in energy use and emissions involved complex tradeoffs. For example, livestock herds were decreased to meet organic housing and stocking density requirements, resulting in reduced emissions, however increasing winter vegetable production with a greenhouse increased energy use (Clark, Khoshnevisan and Sefeedpari, 2016). This case study demonstrates that the individual context of each farm taking on organic transition matters when assessing the impact on GHG emissions and other environmental outcomes.

Canadian experimental data is needed to evaluate the impact of organic production during the transition stage on emissions, including comparisons on a yield or production basis. Scenarios including mixed crop and livestock operations and on-farm energy (such as those modeled in Cooper et al. 2011) could help inform farmers on effective transition plans to minimize emissions while maximizing production under organic management.

GHG Emissions, carbon & global warming potential

Life cycle analysis (LCA) is the gold standard to quantitatively analyze and model the environmental performance of a commercial product through the supply chain (Madhanaroopan & Hammermeister, 2023). LCAs usually assess farm products from cradle to farm gate, and take into account the manufacturing of inputs. For example, an LCA would account for the energy needed to manufacture N fertilizer, and the land required to grow the seed for a crop. Hoffman et al. (2018) found that about 20% of emissions from their conventional systems (no-till and conventional till) were from the manufacturing of N fertilizer.

Organic crops in Canada emit less GHG emissions per hectare than conventional crops. When looking at emissions per kg of product, the results are mixed. Canadian LCAs show that organic crops emit 76% to 125% of conventional crops GHG emissions in CO2 eq per kg of crop produced.

There are only two life cycle analyses in Canada that compare organic and conventional field crops. Pelletier and colleagues (2008) modeled corn, soybean and wheat on a national level and found that organic crops had from 20 to 25% less GHG emissions per unit produced (Pelletier et al., 2008). Viana and colleagues modeled oats in Eastern Canada in 2022 based on one farm that grew both conventional and organic oats (Viana et al., 2022). The emissions per hectare of the organic system were 10% lower, but per tonne of oats, organic emissions were 25% higher. This impact was mostly due to manure transport, fuel combustion increased field activities (eg. tillage) and a higher seeding rate requiring more land for seed production in organic systems.

In Pelletier et al. 's (2008) model, organic production of corn, soy and wheat used only 39% of the energy that conventional crops use, and generated 77% of the emissions. Most of the energy use in conventional production was attributed to fertilizer production, whereas fuel inputs drove energy demand for organic crops. Emissions reduction in the organic field crops came mostly from using green manure compared to synthetic N. Per kilogram, the emissions associated with producing a synthetic N mix commonly utilized in Canada were five times greater than those of producing the same amount of N using green manure cultivation (Pelletier et al. 2008). The model showed similar results for phosphorus, with six times higher emissions for conventional phosphorus fertilizer compared to phosphate rock. The calculations were done assuming organic yields between 90-100% of conventional yields. A sensitivity analysis determined that organic crop yields would have to range from 68-77% conventional yields to produce similar emissions on a yield basis (Pelletier et al. 2008).

Some studies internationally have found similar results. An LCA in Switzerland compared organic and conventional systems with variable tillage and cover cropping practices in a long-term trial running since 2009, growing wheat, corn and field beans (Prechsl et al. 2017). Conventional systems with either tillage method had 80% higher emissions than organic systems per ha. However, when measured per functional unit of food produced, the organic reduced tillage treatment showed higher global warming potential (GWP) due to lower yields when compared to conventional - emissions were not statistically significantly different from each other in conventional and organic systems. GWP is an impact measurement that includes the sum of all emissions and input resources, and is typically expressed in kg CO2 equivalent. This study identified N efficiency as a crucial leverage point.

Organic systems are more energy-efficient. In the Prairies, long-term trials show that organic crop production uses 50% less energy on an area basis than conventional and is 24-40% more energy efficient.

Reviewing the available North American literature for field crops (grains, grain legumes, oilseeds and forages), organic systems require 50% less energy and are more energy efficient per land area and per unit of product for some products (Lynch et al., 2012). Zentner et al. (2011) showed that organic systems in Saskatchewan required only 50% of the energy inputs contrasted with non-organic systems, and were more efficient by 24% (energy output to energy input ratio). At Glenlea in Manitoba (Hoeppner et al., 2006), an assessment of the study after 12 years had similar results: organic had 50% of the energy inputs and were 40% more energy efficient (measured as energy output/energy consumption). These studies also showed that net energy output was lower for organic by 34% and 40% in the SK and MB work respectively. Though energy output was higher in conventional systems (higher yielding, more productive), it was not sufficient to offset the greater energy inputs compared to organic systems. At the time of the publication for Glenlea, they had not addressed the phosphorus (P) deficiency in the organic system, so they qualify the results by saying that the energy efficiency does not take into account the mining of P.

Hoffman et al. (2018) evaluated energy use and GHG emissions of five different field crop systems in Maryland, USA - which varied rotation and tillage practices and were similar to field crop systems found in Eastern Canada. They aimed to account for the impact of fertilizers in organic systems that originated through industrial processes (ie. chicken litter from chickens fed conventionally raised crops and mineral nutrient mining). Energy use on a per area basis was lower in the three organic systems, however on a per kg crop yield basis, it was greater in a two-year organic rotation than the conventional and three-year organic rotations, and lowest in the six-year organic rotation. Similar to the Canadian studies, most energy use came from fertilizer production in conventional systems, whereas in organic systems it was diesel combustion for field activities. They found that total GHG emissions on a per area or per per yield basis were higher in two and three year organic rotations compared to three-year tillage and no-till conventional systems, however lowest emissions occurred in an six-year organic rotation (corn-soybean-wheat followed by three years of alfalfa). In the shorter organic rotations, increased emissions were a result of increased diesel fuel use, and N20 from manure application and crop residues. The largest contributors to GHG emissions in conventional rotations were fertilizer production and application (~55% of emissions) whereas organic system residues accounted for 31-35% of emissions. Moving from a two year (corn-soybean) to three year (corn-soybean-wheat) rotation in organic systems reduced energy use by 6.2% and GHG emissions by 2.7%. Including perennials further reduced energy use 14% and emissions 29%. Perennials decrease diesel needs and increase carbon sequestration. These results indicate that increasing complexity of rotations and including perennials provides a pathway to further reduce emissions in organic field cropping systems.

Indeed, an 8 year study in Iowa concluded that including perennial crops in agricultural systems can reduce energy use and GHG emissions while also increasing productivity (Davis et al., 2012). This experiment didn't test organic management directly, but implemented reduced synthetic N and instead fertilized with manure, demonstrating improvements in emissions and efficiency while moving toward more organic-based practices.

Increasing organic agriculture acreage provides a direct route to overall N fertilizer reduction.

Adopting organic field cropping reduces the emissions related to the manufacture, transport and application of synthetic N. Although they are not captured in agriculture's share of GHGs, they are a contribution in other areas of the NIR that, if reduced, will improve Canada's GHG balance. However, organic agriculture also requires higher seeding rates to outcompete weeds, which can offset some emissions reductions, requiring larger initial land area to grow seed (Viana et al. 2022).

A UK based study simulated winter wheat production across organic, conventional and integrated farming systems to assess energy, land and 100 year global warming potential (GWP) and found that an integrated system provided the lowest GWP and energy use per 1000 kg wheat. The greatest gains in GWP reduction came from not using nitrogen (N) fertilizers and using nitrification inhibitors while maintaining or increasing yields (Tuomisto et al. 2012). Organic farming provides a pathway to make immediate emissions reductions while optimizing other management practices to preserve yield.

Organic N requirements come from green manures or other organic amendments like manure and compost, which vary in their in-field N2O emissions. The use of green manures, when compared to N fertilizer as a main source of soluble N for the crop, can lead to reduced field-level N2O emissions. The green manure adds additional non-harvested biomass to the system, leading to the possibility of sequestering carbon, and removes the emissions associated with fertilizer N. Growing season precipitation has a key influence on N20 emissions

In a 2020 review of literature around emissions factors, Walling and Vaneeckhaute found that there is little consensus around the impact of organic amendments on N2O emissions compared to conventional fertilizer. Indeed, overall emissions from organic amendments will differ depending on several factors - for example animal age, type, weight and diet for manure. This highlights the need for context-specific emissions factors of GHG in agricultural systems to accurately assess the impact of different management practices.

D'Amours et al. 2023 assessed the impact of organic management on GHG emissions in Quebec, directly measuring GHG fluxes in soil throughout the season. They determined that on sandy loam, manure will have higher N2O emissions than inorganic fertilizer, because denitrification in these soils is thought to be limited by labile C. On a per area basis, combined best practices of reduced tillage (chisel plough vs moldboard plough) and green manures instead of livestock manure reduced N20 emissions and global warming potential. However when evaluated per unit of yield, there were no statistically significant differences in 2019, and a small difference in 2020 (0.32 and 0.09 g N20-N/kg grain DM in moldboard ploughed with poultry manure and chisel ploughed with green manure, respectively). Overall, emissions were much higher in 2019 compared to 2020, 2020 was dry at the time of fertilization which lends itself to low emissions. Highest emissions occurred when water-filled pore space was greater than 50% and low when less than 30%, irrespective of NO3-N in soil. In this farm's context, green manures may have induced slower N release from mineralization timed better for crop requirements compared to livestock manure systems (D'Amours et al., 2023).

Moisture was also a major factor of GHG emissions in wet years at long-term organic and conventional trials at Glenlea in Manitoba. Fall moisture impacted subsequent N2O emissions in spring thaw (Westphal et al., 2018). Having an overwintered cover crop can reduce spring thaw-related N2O emissions (Wagner-Riddle & Thurtell, 1998).

Organic systems have more soil C inputs

Without the use of synthetic fertilizers and pesticides, organic farms must implement practices that are known to build soil organic matter and add carbon: diverse crop rotations, cover cropping, green manuring and including perennial crops.

In a 2023 review of LCAs comparing conventional and organic practices, Boschiero et al. found many researchers identified these practices contributed to soil organic carbon (SOC), which helped to reduce the impact of agricultural production on climate change. This impact was particularly pronounced in organic farming, because of the larger carbon inputs from biomass and organic fertilizers.

A study associated with the Maryland-based experiment of Hoffman et al. (2018) found greater soil carbon in the six year organic trial compared to conventional tillage and no-tillage plots - the organic treatment were a net sink for carbon and conventional treatments were net sources of CO2 (Cavigelli et al., 2009). They concluded that practices typical of organic production, such as soil incorporation of cover crops and manures, mitigate global warming potential and greenhouse gas intensity compared to conventional systems due to increased soil carbon (Cavigelli et al., 2009).

Long term trials from 1981 to 2002 in Pennsylvania found significantly greater soil carbon (soil organic matter) in organic systems compared to conventional systems, and found soil carbon increased over the length of the study in the organic trials (Pimentel and Burgess, 2014).

In a global review of 74 studies, mostly in temperate climates, that looked at pairwise comparisons of organic and conventional systems, there were higher SOC concentrations, stocks and sequestration rates in organic systems (Gattinger et al., 2012)

In addition to primary C sequestration, research definitively shows many secondary interrelated co-benefits of increased carbon in soil, which will be discussed further in the soil health section of this paper.

Downstream emissions are rarely quantified in the literature.

LCAs typically account well for inputs and on-farm activities, however post-harvest can be less clear. Cooper et al. (2011) emphasize the importance of defining meaningful boundaries by accounting for the impact of differences in processing and end uses on emissions. For example, scenarios including bio-energy recovery from on-farm bio-gas systems offset 410 kg CO2/ha in the organic system and 451 kg CO2/ha in the conventional system, or 12% of total emissions in organic and 6% in conventional. Defining boundaries and end-use impacted total emissions of each scenario - for example on-farm feeding of dairy cows led to 173.6 kg CH4 and 155 kg CH4 emitted for organic and conventional cows, respectively. However, crops sold for feed off-farm and designated for pig production, had 1.65 kg CO2/kg pork.

Long term field experiments in Denmark found that two different organic scenarios had similar carbon footprints as conventional management, however an organic rotation where a green manure is harvested and used for biogas had a lower carbon footprint (Knudson et al. 2014).

What is the end-use of most organic grain in Canada? How do those end-uses contribute to GHG emissions and other environmental impacts?

Do organic systems use more cover crops than non-organic systems, thereby tending to reduce spring thaw N2O emissions?

What might it look like to use livestock manure to meet P needs, and rely on green manure for N? What are the results of a mixed livestock & legume approach to organic fertility?

Transportation: For organic farms in Canada, how far is manure travelling? Are there more integrated livestock/field crop operations in the organic sector compared to conventional?

More details from Swiss studies? Skinner et al. 2019?

Co-benefits

Organic agriculture - or practices common in organic farming - have the potential to improve a whole host of environmental, economic and social factors. In an analysis of 43 agroecosystem properties, researchers have shown that organic and conservation agriculture promoted ecosystem multifunctionality, especially by enhancing regulating and supporting services, including biodiversity preservation, soil and water quality, and climate mitigation (Wittwer et al. 2021).

Yields and Prices

Organic producers can expect lower yields and higher prices for their crops.

There is a yield gap between conventional and organic crops, primarily due to nutrient availability differences due to N and P fertilizer use in conventional agriculture along with pesticide use to reduce weed competition and insect or disease pressure. Globally, across all crops, organic crops on average have 19-25% lower yields (Ponisio et al., 2015; Seufert et al., 2012). LCA studies contrasting organic and conventional systems over the past ten years, have global average yield gaps, for field crops relevant to Canada, of 24% (Boschiero et al., 2023).

For N-fixing crops such as soybean and other pulses, the gap is less pronounced (Seufert et al., 2012), with some authors considering it to be non-existent (Pelletier et al., 2008). Leguminous plants fix their own N and can perform better compared to non-legumes in organic systems. The smaller decline in yield for organic compared to conventional pulses is due to lack of soluble P and weed incursion into organic fields without herbicides as a tool. Alvarez (2022) suggests that legume crops' yield gap is on average 10% while cereals are approximately 30%.

The yield gap between organic and conventional was reduced to 5-13%, smaller than the reported average, when best management practices were used, such as increasing rotation diversity and length, and using green manures (Ponisio et al., 2015; Seufert et al., 2012). This highlights the importance of further research and promoting and improving best practices within organic farming.

Another factor that decreases the effective yields of organic crops is that land and time is dedicated towards fertility and building the soil. Although it may be possible to meet conventional yields within a year, once the whole rotation is accounted for, the harvested yields for the whole period can be lower. In some organic field crop systems in Canada, an N fixing green manure will be grown for at least one year of the crop rotation, reducing the yield potential compared to continuous cropping.

However, diversified rotations that may reduce overall yield provide other net benefits. For example soil health, biodiversity, and pest control all improve with the inclusion of perennials, green manures and cover crops (Benaragama et al., 2022; Franco et al., 2021). Organic producers included more years under pasture, fallow or cover crops in their rotations than conventional producers (29% vs. 12%) in a 2022 quantitative review of 90 papers covering 60 experiments from mostly across the USA and Canada (Alvarez, 2022) so we can expect those co-benefits to be captured more frequently in organic production.

In Canada, comparisons of organic and conventional yields reflect the global findings.

In the region of Montérégie Quebec, the yield gap is about 21% for grain corn and 15% for soybean, a primary region for field cropping. From 2016-2021 organic grain corn yields were 8 t/ha (FADQ, no date) and overall corn yields were 10.1 t/ha (Institut de la statistique du Québec). For soybeans, for the same region and period, yields were 2.8 t/ha and 3.3 t/ha for organic and overall, respectively. This represents an estimated yield gap of 21% for grain corn and 15% for soybean. Note: The overall, "conventional" total includes organic, at a scale of 14,824 ha of organic cereals and oilseeds in Montérégie *(Portail Bio QC)* compared with a total of 776,180 ha total cereals and oilseeds (Institut de la statistique du Québec) for the "conventional" total – i.e. organic ha are just under 2%.

In Ontario, comparing OCO numbers to StatCan provincial averages shows a yield gap of 28%, 24% and 34% lower yields for organic corn, soybeans and wheat, respectively. The Organic Council of Ontario estimates provincial "benchmark" organic yields as slightly higher than the Agricorp 5-year average – corn at 7.5 t/ha, soybeans at 2.5 t/ha and wheat at 3.7 t/ha *(OCO Organic Field Crops COP Budget Calculator)*. A 5 year overall average (2018-2022) of Ontario yields of these commodities from StatCan shows 10.4 t/ha for corn, 3.3 t/ha for soybeans and 5.6 t/ha for wheat.

Saskatchewan is the province with the most organic acres in Canada, with dominant crops of wheat, lentils and flax. There is no yield data available for this province.

The organic premium in Ontario is between 150-225% of the conventional price (OCO, no date). Data from *OrganicBiz*, which updates the organic prices and premiums of field crops regularly (the organic premium indicates the excess value organic prices contrasted with conventional prices). **In the Prairies, a snapshot for the week of February 14th 2024 shows organic premiums of 150-360% for field peas, flax, lentils and wheat** *(Organic Grain Hub and Saskatchewan Specialty Crop Prices)*.

Another upside of organic production is lower input costs). This is balanced with a higher labour requirement. In the Rodale corn-soy rotations (reasonably comparable to Canada's

Eastern corn-soybean systems), they found that 35% more labour was required than the conventional system, but it was more evenly distributed throughout the growing season (Pimentel & Burgess, 2014).

More land is required when crops are grown organically. On an overall basis, assuming that the same amount of food needs to be produced, with lower yields, organic needs more land to do the same volume. Although it is clear that a growing global population requires more food, it is not clear that the only way to provide that food is by producing more. Food waste reduction, improved food distribution, more plant-based diets (less acreage required for livestock feed) and other social tools can be implemented to reduce demand for farmland acres.

Soil Health

Increased soil carbon improves soil health

Soil carbon or soil organic matter is often understood to be practically synonymous with soil health. Soil organic matter is the dead and decomposing material of formerly living organisms. As such organic matter inherently contains the nutrients that support the organism as well as carbon-based molecules. Together, organic matter is an important source of energy and nutrients for soil life, which in turn, decompose and release nutrients to be taken up again by plants. The presence of organic matter in the soil also serves many other roles including: holding nutrients and improving cation exchange capacity, improving soil aggregation (structure) which improves water and air infiltration and reduces both compaction and soil erosion, holding soil moisture.

Early data from the Harrow Agriculture and Agri-Food Canada research site found organic matter was at “at least maintained and may have slightly improved” in an organic soybean-winter wheat-corn rotation including hairy vetch, crimson clover and red clover cover crops (Belanger and Yang, 2023). There is potential to maintain or increase SOM with organic management in Canadian cropping systems.

In the previously mentioned long-term trials at the Rodale Institute in Pennsylvania, Pimentel and Burgess (2014) compared a typical conventional corn-soybean rotation with an organic rotation typical of a mixed livestock-integrated farm (corn, soybeans, corn silage, wheat and red clover hay, rye cover crops) and an organic system with green manure for most fertility needs (hairy vetch, corn, rye, soybean, winter wheat). They collected lysimeter data on soil and found that SOC was statistically the same for all three treatments at the beginning of the experiment in 1981, but by 2002 organic systems had statistically significantly more SOC than the conventional.

Organic farms were found to have over twice the percentage of soil organic matter in a study comparing 30 organic mixed vegetable farms with 10 conventional benchmark farms in Michigan (Kaufman et al. 2020). Of the 30 organic farms 24 had measured increases in soil organic matter, and five reported decreases. Those farms showing increases were found to have started with low soil organic matter and thus it had been improved, and tended to have shallower tillage practices. Those showing a decrease in soil organic matter were found to have started with a high soil organic matter content when initiating organic production or had management practices with deeper tillage. This study illustrated the importance of tillage dynamics on soil organic matter content, but also demonstrated that organic farming can regenerate degraded soils.

Marriott and Wander (2006) took soil samples from nine different farming system trials across the USA comparing conventional and animal manure or green manure-based organic systems. They found that across all sites, organic management significantly increased soil organic matter (14% averaged across all sites) and total N, compared to conventional systems.

An increase in SOC or soil organic matter leads to improved soil structure, wet aggregate stability, porosity and biology, further leading to a host of tertiary and cyclical improvements to crop development. This also reduces erosion potential of soils.

Auerswald, Kainz and Fiener (2003) modeled soil erosion on organic and conventional farms across Bavaria, and verified with experimental data. They found that organic agriculture tended to take place on more erodible land (no evidence of this in Canada), so if left fallow the authors predicted 14% more soil loss on organic soils. However, if site conditions were identical, organic cropping practices integrated more protective management (for example including perennial grasses and legumes), so organic agriculture would cause 24% less erosion. Combining site and practice data across Bavaria, average soil loss was modeled at 15% less for organic agriculture compared to conventional - their verification data agreed.

Practices common to organic production contribute to improved soil health

In a study of 34 farms (20 conventional and 14 organic) in Atlantic Canada, Mann et al. (2019) assessed the impact of specific management practices on soil health indicators. Certain practices common to organic production, such as rotational diversity including perennials and manure application were associated with positive physical and biological characteristics like soil respiration, wet aggregate stability, non-mycorrhizal fungi, AMF and Gram negative bacteria. However, no direct comparison was made between organic and conventional farms holistically.

Canada’s oldest organic crop rotation study, Glenlea in Manitoba, helped parse some of the dynamics of soil health under organic management. In 2001, Nelson found less total soil carbon but higher wet aggregate stability in organic grain-only plots. Wet aggregate stability has typically been associated with soil carbon or soil organic matter, however in this case is attributed to greater microbial biomass or living carbon in the organic plots (Entz, 2022).

However, most soil tests only look at the top 30 cm of soil. Bell et al. looked at 18 years of Glenlea data comparing organic and conventional production of two different rotations: annual crop rotation (oats-soybean in conventional, faba bean green manure in organic-wheat-flax) and alfalfa crop rotation (wheat-flax-alfalfa-alfalfa). All crop residues were ploughed under and no manure was applied to organic crops. They found no difference in SOC from 0 to 120 cm or N from 0-60 cm between organic and conventional management of similar rotations. There was a greater organic C concentration in the alfalfa crop rotation when farmed conventionally in the 0-15 cm and 90-120 cm depths, and in the conventional annual crop rotation for the 90-120 depths compared to the same rotation farmed organically. This can likely be attributed to lack of manure inputs and lower yields in organic meaning less crop residue as carbon biomass input (Bell et al., 2012). We can observe that gains in soil carbon to a depth of 120 cm likely come from diversified rotations including perennials, and manure application - both practices common to organic crop management in

Canada. The researchers plan to repeat the deep soil C assessment in 2024, and that will enrich the dataset and provide more information on how organic farming affects soil C stocks. Since the Bell study, we split some of the plots and are adding compost (at P requirements) to some organic subplots.

Reducing tillage in organic agriculture to improve soil is possible and is a priority

Reduced tillage is often associated with positive soil health indicators (Mann et al., 2019) and tillage intensity is sometimes increased on organic farms to manage weeds without use of herbicides.

Indeed, a commonly raised critique of organic farming is the erosion risk from increased tillage. In 2003 and 2004, Nelson, Froese and Entz completed a mail survey of organic and conventional farmers from Alberta, Saskatchewan, Manitoba, Ontario, Nova Scotia and New Brunswick, with most respondents located in the Prairie provinces. Approximately 60 and 80 percent of organic and mixed conventional and organic producers reported growing forages, compared to only 46% of conventional farmers. In an even more striking difference, 84 and 73% of organic and mixed organic and conventional farms utilized green manures, compared to only 6% of strictly conventional operations. Though more conventional farmers reported practicing zero tillage, a larger proportion of organic farmers were practicing alternative forms of conservation tillage (eg. ridge tillage) - leading to an overall statistically similar proportion of each group using reduced tillage practices. Similar proportions of each group reported applying manure, however a greater proportion of organic producers applied compost (56% of organic farmers vs. 9% of conventional). A greater proportion of organic farmers reported using shelterbelts and grassed waterways compared to conventional respondents, however overall averages reported in this survey were greater than national averages, indicating that there may have been a bias towards respondents answering the survey that already engaged in soil-protective practices. Overall, responses indicate that both organic and conventional farmers in Canada are engaging in practices to prevent soil erosion and preserve soil structure.

A study in the Netherlands evaluated reduced tillage in two organic rotations and one conventional rotation on a clay loam over four years (Crittenden et al., 2015). Annual precipitation was closely comparable to Eastern Canada, however the rotation included wheat with root crops (carrot and potato) uncommon to Canadian field crop rotations. They found that non-inversion tillage either improved or imposed no penalty on crop yields in organic rotations, and improved soil aggregate stability, penetration resistance, and soil organic matter in the top 10 cm. This indicates potential to reduce tillage in organic systems while improving soil structure and maintaining crop yields.

Organic agriculture can lead to increased soil microbial biomass and biodiversity

An organic trial at Victoriaville, QC, revealed an increase in the abundance of earthworms by 618% during organic transition (Gagnon Lupien et al., 2020). Similarly, in a study of soil health under organic potato production, the rotational effect of increasing on-field biodiversity showed significant increases in earthworm abundance from 73.5 to 493.5 (Nelson et al., 2009). Microbial biomass was also significantly increased during the rotational phase, indicating on-field complexity contributes to the health and diversity of soil fauna (Nelson et al., 2009).

Microbial biomass was found to be greater in organic rotations that included forages when compared to conventional, but lower than conventional in grain only rotations (Braman et al., 2016). *Nelson et al. (2011)* attributed greater microbial richness and diversity under organic wheat management to soil management and history of compost use, plus greater weed populations. Soil enzyme activity was highest for organic systems, particularly when they included forages (Entz, 2022). They also found greater increase in microbial biomass phosphorus after soil rewetting compared to conventional systems. Samples at this site also revealed more neutral pH in organic soils compared to conventional, which supports Proteobacteria (Li, 2012; Entz, 2022).

Pimentel and Burgess (2014) posit that not using synthetic pesticides minimizes harmful effects on non-target organisms. Their organic rotations were found to have greater populations and greater colonization of arbuscular mycorrhizae fungal networks that enhance plant uptake of nutrients, when compared to conventional counterparts.

As previously noted, a long term study in Manitoba reported that organic management increased microbial biomass carbon in a rotation that contained perennial forages compared to conventional (1718 vs 1476 μg/g) but the reverse was true in an annual grain crop rotation (Braman et al. 2016). When looking at all soil biological parameters, only an organic rotation that included perennial forages was similar to restored prairie grassland - indicating organic management combined with perennials can mimic natural habitat for soil biology.

Pérez-Guzmán et al. (2020) compared 18 years of continuous silage corn, continuous soybean and perennial grasses in Ontario. Perennial grasses had up to 8.1 times more arbuscular mycorrhizal fungi, increased fungal/bacteria ratios and higher microbial diversity. All soil health indicators were worse under monocultures. Though this study did not compare organic and conventional treatments, monocultures are extremely uncommon in organic agriculture, and therefore we can expect to see the biological benefit in more diverse rotations common to organic farms.

A long-term field study in Switzerland compared organic and conventional production in a region with similar mean precipitation to agriculture in Eastern Canada. The crop rotations were initiated in 1978, and in the 1992 and 1993 seasons researchers found that earthworm biomass, density and population was greater in organically managed plots (Siegrist et al., 1998). Researchers attributed this impact to livestock manure for fertility.

Ongoing research works to evaluate the connection between soil health and organic farming, including opportunities to optimize soil biology, control soil-borne diseases, and evaluate appropriate soil health tests for organic agriculture.

Working to optimize soil biology in organic field crops, Marshall and Lynch (2020) investigated different termination methods of green manure in organic grain rotations and the impact on soil life. The researchers measured microbial biomass, earthworms, beetles and spiders for three years post hairy vetch and oat termination via no-till methods, spring tillage, and fall tillage as well as red clover fall tillage termination. They found soil microbial biomass was impacted more by green manure species rather than termination. The greatest impact occurred right after tillage, dissipating within two months, except earthworms which were affected for two full years (Marshall and Lynch 2020).

In a review of existing literature about managing residue and organic amendments to manage soil-borne diseases, Bailey and Lazarovits (2003) report that manures and composts rich in N release allelochemicals during storage or microbial decomposition that may reduce soil-borne diseases through ammonia liberation. They observe a promising trend that high N organic amendments reduced populations of plant pathogens, but increased soil bacteria and fungi. This supports an additional proposed mode of action - organic amendments increase soil microbial populations, which in turn may suppress and out-compete pathogenic growth. Examples of success include meat and bone meal, soybean meal and poultry manure reducing incidence of verticillium wilt, potato scab and parasitic nematodes, and liquid swine manure killed V. dahliae which causes verticillium wilt, while the population density of remaining soil organisms increased.

Another review looked at 2423 studies to assess soilborne disease suppression using organic amendments and expanded on that work, identifying that enzymatic and microbial parameters tend to be most effective in predicting suppressive organic amendments (Bonanomi et al., 2009). Fluorescein diacetate (non-specific enzyme activity), substrate respiration, microbial biomass, culturable bacteria, fluorescent pseudomonads and *Trichoderma* populations are most predictive factors. Entz's (2022) reporting of higher enzyme activity in organic soil in Manitoba could indicate that soils may have some protective capacity against disease.

Researchers have worked to optimize soil health testing and interpretation in Nova Scotia (Marshall et al. 2021) and specifically on organic farms in Ontario (Hargreaves et al., 2019), providing opportunities to identify crop management practices most likely to continue to positively impact soil health in Canada.

Studies may not automatically show a direct benefit to soil health when comparing organic and conventional farms using identical practices - however organic and conventional farms rarely (if ever) use identical practices. Growing crops organically necessitates the use of specific management practices that have been empirically demonstrated to boost soil properties. Organic farming necessitates diversified rotations and other soil-building practices.

With most agricultural research focused on chemical or synthetic products that one can brand and trademark, gains in plant protection and soil health have likely been left in the field when it comes to optimizing organic amendments. Supporting organic agriculture research in Canada can help optimize soil health while preserving crop yields, resulting in great environmental and economic benefit.

Biodiversity

Recent meta analysis indicated that organic farming had a 23% gain in biodiversity (species richness) compared to conventional farming over many taxa including microbes, invertebrates, plants and birds (Gong et al. 2022). Often the tradeoff was lower yield, but the relationship between scale of biodiversity gain and yield loss was not linear, and in non-cereal scenarios, biodiversity increased in organic systems without yield loss compared to conventional systems (Gong et al., 2022).

Moreau et al. (2022), reviewing the literature, found that at each level of the food chain (i.e. primary producers: weeds/seeds and first- and higher-order consumers:

invertebrates/vertebrates), resource abundance and/or diversity are greater on organic farms.

Bird and plant biodiversity is greater on organic farms in Canada compared to conventional farms

Agriculture in general, disturbs natural habitats and is detrimental to the species diversity of birds compared to nature preservation. The impact of agriculture on bird biodiversity varies across Canada - with greater declines in species in the East than in the Prairies (Betini et al., 2023). Researchers hypothesize that birds in the Prairies are more adapted to open habitats. In the Pacific area, agriculture had less of an impact, maybe due to the lowest proportion of farmed land, and maybe due to the nature of the crops grown (e.g. more tree fruit) (Betini et al., 2023).

Around Peterborough Ontario, Boutin et al., (2008) found that organic farms had more plant species in crop fields and hedgerows, several of which were important for conservation purposes and only found on organic farms.

In Ontario, at 72 field sites, comparing 10 conventional and 10 organic farms it was found that species richness and abundance were significantly greater on organic farms (Freemark and Kirk 2001). This was attributed to non-crop habitat on organic farms, with greater landscape heterogeneity, more pasture, and more winter grain.

More recently, Kirk et al. 2020 compared organic and conventional fields in Saskatchewan, Ontario and Quebec and found that organic farming had a more positive impact on breeding season bird abundance compared to conventional farming. The influence of organic farms was most positive in regions with most intensive agriculture ie. biodiversity of birds may increase the most when organic ag is implemented in areas that are mostly large-scale intensive operations with less surrounding natural habitat.

Eliminating pesticides has been linked to increased species richness and abundance.

In Victoriaville, Quebec during the transition period to organic, they recorded an increase in the plant species richness in the field margins, especially flowering plants. This translated to a 750% increase in bees after the first year. This was attributed to the cessation of herbicide use. They also found that spider abundance in the field margins increased by 356% in the third year of transition. They also measured carabid beetles, but there was no change in their population over the 3 years (Gagnon Lupien et al., 2020).

In the prairie parklands area of Saskatchewan, Kirk & Lindsay, (2017) compared bird species on 10 matched farm pairs and found that birds were more abundant on organic farms, but the number of species were the same on organic and conventional farms. The factors that were most influential were the amount of native grassland and woodland, including shelterbelts and wetlands, within a 16.3 ha area. Aerial insectivores were the class of birds most favored by organic farms. After field extent land cover, other influences were seed treatment, herbicide use and number of passes (all field operations).

In the UK, McKenzie et al., (2011) set up a replicated, randomized trial that investigated bird visits to cereal stubble over 3 years. They found that pesticide use was associated with less bird foraging on conventional plots. To a lesser extent, the use of inorganic fertilizer was identified as a factor reducing bird visits.

Henderson et al., (2009) set up a 6 year experiment in the UK to test the impacts of fertilizer, pesticides (insecticides and herbicides in this case), and of increasing crop diversity. The pesticide reduction had a positive effect on bird populations for some species in some seasons, as well as a significant impact on carabid beetles.

Morandin and Winston (2003) found that compared with organic canola, bee abundance decreased and pollination deficit increased with conventional and especially GE canola – as weed abundance decreased. Thus herbicide use to eliminate weeds was correlated with decline in bee abundance and pollination.

Organic farms may contribute more to heterogeneity which improves biodiversity.

Landscape heterogeneity plays a big part in biodiversity (birds, mammals, flora, invertebrates) (Benton et al., 2003). Smaller farms, smaller fields, more non cropped areas (field boundaries, hedgerows, riparian areas, woods), and more plant structural heterogeneity all encouraged more biodiversity. Studies as well as the leading existing program for environmental planning on Ontario farms, highlights increasing landscape configurational heterogeneity and connectivity, to provide habitat and accessibility to resources for wildlife (Fahrig et al., 2015; Vandermeer and Perfecto, 2007).

Organic farms tend to have more of these heterogeneous features and therefore, more biodiversity. (Benton et al., 2003; Smith et al., 2010; Alvarez, 2022).

In Eastern Ontario, Fahrig et al., 2015 found that smaller fields meant more biodiversity: birds, plants, butterflies, syrphids, bees, carabids and spiders. Belfrage et al. (2005) found dramatically more bird and herbaceous plant species, butterflies and bumblebees on small farms than large farms in Sweden.

Can we show with data that organic farms tend to be smaller or have smaller field sizes? Anecdotally I'd say that's the case in Ontario - related to farmers who come from non-farming backgrounds not having access to generational land.

Temporal heterogeneity - i.e. more complex crop rotations - also positively impacts biodiversity.

In Eastern Ontario, Girard et al., (2014) looked at insects on the soil surface that are food for ground-foraging birds (nestlings specifically). The insect biomass on organic farms was 43% higher than on conventional farms in June and 35% higher in July. The differences were not due to increased weed biomass. Instead the authors indicate that increased crop rotation diversity, and possibly the presence of manure and absence of herbicides, were the drivers for increased insect biomass on organic farms.

Henderson et al. (2009) tested increasing crop diversity – adding 14% natural set-asides, oilseed rape, spring wheat and peas to a rotation that had previously been about 90% winter wheat. The crop diversity had an immediate and significant positive effect on bird populations, including species of conservation interest.

Organic management is more likely to increase biodiversity in simple landscapes (Gabriel et al., 2013) such as in the Prairies, but the biodiversity benefits may be smaller in more heterogeneous landscapes with smaller fields and more natural habitat (Bartary et al. 2013). In a side by side digital comparison of over 70 pairs of organic and conventional fields in Saskatchewan, Xu (2021) found that overall area of semi-natural features of mixed perennial vegetations was higher in organic (9.31%) than conventional (6.06%) fields. However, this result varied across ecoregions with larger differences found in the cooler and wetter parkland region ranging to no difference in the dry mixed grassland region. The differences resulted from greater cultivation of depressions (wetlands and lowland areas) which were less likely to be cultivated on organic fields. Although shelterbelts were not very common overall, shelterbelts were more likely to be present on organic fields. These observations were hypothesized to be a result of a combination of a) mechanical tillage being less feasible for managing wet lowlands compared with use of herbicides by conventional operators, or b) a tendency for organic farmers to have a greater appreciation for habitat conservation, and/or c) organic farmers being of smaller scale on average having smaller equipment to navigate around depressions and shelterbelts.

Organic agriculture can be seen as a 'land sharing' method of preserving biodiversity.

When considering the environmental impacts of agriculture, the tradeoffs are sometimes framed as 'land sharing' - developing agricultural systems that emulate nature that are more extensive - or 'land sparing' - intensifying agriculture to meet yield needs on less land, converting less natural land to agriculture in the first place. The latter approach must also account for flows of excess pesticides and nutrients within a bioregion.

The individual context of the area is of predominant importance when discussing land sharing and sparing. Since it has been concluded that relative benefits of intensive and extensive farming are dependent on how much cropped area there is in an area, planning could be improved in already predominantly agricultural landscapes (Egan and Mortensen, 2012). Areas with very little non-cropped land can benefit hugely from even small amounts of completely undisturbed land, so land sparing may be the best approach, whereas areas that already have high amounts of uncropped land may benefit more from land sharing to maintain species richness (Egan and Mortensen, 2012).

Water quality and availability/use/cycling/dynamics

There is a dearth of data on the relative impacts of organic versus conventional agriculture when it comes to impact on watersheds. It is challenging to directly compare conventional vs. organic production in single-year studies because of the nature of management styles and inputs. Conventional inputs tend to be tailored directly to the specific crop and year, whereas organic inputs like manure are often included as part of an overall, multi-year rotation. So, there may be more nutrient loading in a single fertility event in organic production, but that is not representative of the every-year impact of the rotation.

However, it is clear that conventional agriculture, through its sheer scale and input intensity, has had severe negative impacts on water quality. Some highly visible examples include cyanobacteria blooms in Lake Erie caused largely by agricultural P and the hypoxic zone in the Gulf of Mexico, caused by nutrient loading along the Mississippi River (e.g. Freyereisen et al. 2022; NCCOS 2024; Stumpf et al. 2012; US EPA 2025;).

Viana et al.'s (2022) LCA showed that organic production had worse outcomes for nitrate (marine eutrophication) and phosphorus (freshwater eutrophication) compared to conventional agriculture. Marine eutrophication was 54% worse /tonne, 10.1% worse per ha and 13% better per 1000 CAD gross income. However, they also reported that organic production was 87% better than conventional in terms of overall water consumption.

A study of 15 organic dairy farms in Ontario found that farm nutrient loading and risk of off-farm losses to air and water are greatly reduced under commercial organic dairy production compared with more intensive confinement-based livestock systems (Roberts et al. 2008).

At the Rodale Institute in Pennsylvania, water volumes were higher in two organic treatments compared to conventional, indicating groundwater recharge and reduced runoff (Pimentel and Burgess, 2014). Nitrate leachate was above the regulatory limit of 10 ppm in 20% of samples from conventional treatments, and 10 and 16% of samples from organic-animal manure-based systems and organic green manure-based systems, respectively. - variation was mostly dependent on the intersection between weather conditions and available N. When a drought followed a high-N green manure crop, the following crop yields were low, leaving excess N in the field, which was leached in heavy fall rains.

Boschiero et al., 2023 note that few LCAs compare the impact of organic and conventional systems on water. For studies that did take water into account, water use varied by crop type and was lower on average in organic systems but not statistically significant.

Individual studies comparing carrot production in Poland and cacao production in Bolivia reported reduced water use and increased water efficiency in organic compared to conventional production (Kowalczyk and Kubon, 2022; Armengot et al. 2021). A more general study in China also found that the water footprint was lower in organic farming compared to conventional methods (Feng and Zhao, 2020).

Similar to soil health, we may not see studies that directly assess improved water quality and availability in Canada by replacing conventional agriculture with organic methods. However, soil health is directly tied to water quality and is described by Bünemann and colleagues (2018) as the ability of the soil to foster plant growth, regulate water infiltration and prevent water pollution, thereby promoting groundwater recharge and protecting watersheds. As organic farms often have higher SOC and SOM, the primary indicators of soil health, it is reasonable to expect organic farms to have better water quality and quantity.

As discussed in the biodiversity section, organic farms tend to have more landscape heterogeneity, including more shelterbelts and conserved wetlands. These buffers are generally understood to improve water quality (e.g., Dosskey et al. 2010; Douglas-Mankin et al. 2021; Muñoz et al. 2024), but there is some variability in efficacy (e.g. Cole et al. 2020; Randall et al. 2015).

Therefore, despite a lack of direct evidence, organic production practices, many of which are the same ones that enhance soil health and biodiversity, aim to reduce nutrient leaching, soil erosion, and runoff, thereby improving water quality.

Is there more Canadian data that we missed?

Climate change adaptation

Drever and colleagues (2021) strove to identify climate change mitigation strategies specific to Canada. For agricultural pathways, they identified practices like cover cropping, increased biodiversity with trees, inclusion of legume crops, reduced synthetic N fertilizers (Drever et al., 2021) - practices and features common on organic farms. Organic agriculture strives to mitigate climate change through reductions in emissions and sequestration of carbon, but opportunities exist for adaptation as well.

“On the adaptation side, organic agriculture systems have a strong potential for building resilient food systems in the face of uncertainties, through farm diversification and building soil fertility with organic matter.” (Scialabba and Lundenlauf, 2010).

In the face of a less predictable and more extreme climate, agricultural systems that are diverse will show the most resilience in yield and profit stability.

The Farming Systems Trial (FST) began in 1981 at the Rodale Institute in Kutztown, Pennsylvania comparing manure-based organic, legume-based organic and conventional farming. Averaged over 30 years, there were no differences in corn and soybean yields in tilled systems, however in four out of five drought years, yields were higher in both organic rotations (6938 kg/ha and 7235 kg/ha) than conventional yields (5333kh/ha) (Siedel et al. 2017). Researchers attributed the higher yields to better water holding capacity in the organic plots (Lotter et al., 2003). Overall, the organic systems in FST (both tilled and no-till) led to greater profitability (Seidel et al., 2017).

Through long-term trials it has been shown that more complex rotations including three or more main crops or cover crops show more resilience through periods of stress, and increased yield stability (Gaudin et al., 2015). Forage legumes included in a corn and soybean based rotation over time were shown to increase mean corn and soybean yields by 6 and 13% respectively, and when compared within a particularly hot and dry period, rotations including alfalfa had 8.7% higher corn yields than a corn-soybean rotation (Gaudin et al., 2015). An 8-year study in Iowa found that more diverse rotations with reduced chemical inputs had grain yields and profits similar to or greater than a conventional two-crop rotation (Davis et al. 2012).

Reduced reliance on synthetic inputs protects organic farmers from economic insecurity in the face of climate change.

Raising crops and livestock organically offers alternatives to synthetic inputs and higher income options for farmers. This reduced dependency on energy and synthetic inputs reduces vulnerability to rising costs - prices for things like fertilizer N and fuel spike and increase in uncertainty with climate change (Scialabba and Lundenlauf, 2010, Muller et al. 2016).

Because synthetic inputs are produced by multi-billion dollar companies, many research dollars have been dedicated to make even incremental gains in yield. The less-commercial aspect of organic agriculture has historically meant less research dedicated to optimizing agronomic management in these systems - which could mean the potential for large gains in total yield, and yield resiliency and stability. For example, in a Swiss farming systems and tillage experiment, researchers investigated the impact of cover crops on corn and wheat yields (Wittwer et al., 2017). On average, incorporating cover crops improved crop yield of corn and wheat by 24 and 13% in reduced tillage and tillage organic systems, respectively, compared to 8% and 2% in conventional reduced tillage and tillage systems. Opportunities exist to continuously improve holistic and organic management strategies.

Livestock

Organic livestock plays an important role in increasing certified organic acres. Organic livestock must eat organic feed and are therefore an important market for organic grains. Canada currently has about 780 certified organic livestock operations, but the number has declined since 2019. There are significant barriers to certification for livestock farms which, if addressed, could elevate the entire organic supply chain.

On Quebec dairy farms – preliminary evidence reported in the news showed a 45% reduction in CO_2 eq/ha, but this may not include enteric methane. In a case study from the Maritime provinces, the main barrier for livestock producers to certify their animals is the regional availability of organic feed (ACORN conference, 2023). The only organic feed mill in the region does not deliver in bulk to farms, so their feed is not accessible for commercial-scale customers. The cost and logistics of importing bulk organic feed from Ontario or Quebec are prohibitive to most.

Organic livestock production systems, when excluding the production of feed, have a mixed impact on GHG emissions. When the feed's impact is considered (i.e. in LCA studies), there is a reduction of GHG emissions on organic livestock farms compared to conventional livestock farms. The reduction is again associated with reduction of N fertilizer for feed production and comes from the manufacturing of N fertilizer.

In an LCA of Canadian egg production Pelletier (2017) found that organic eggs showed less resource use and emissions intensity compared to a range of other housing (conventional, enriched, free run and free range). This was attributed to superior performance of organic feeds. Since this study, the Canadian egg industry updated its housing standards, and researchers published an updated LCA with information from 2019 reporting reduced emissions across housing. Organic production continued to have the lowest impact for nine out of ten environmental impacts - including further reduced acidifying, eutrophication and GHG emissions (Turner et al. 2022).

In contrast, an Italian case study comparing conventional and organic beef reported that organic farms produced more GHG emissions than conventional (24.63 and 18.21 kgCO_2eq/kg live weight respectively) mostly attributed to enteric fermentation (Buratti et al., 2017). An important caveat is that this study did not take into account emissions from feed production, but authors suggested that improved feeding strategies could reduce methane emissions in organic production.

In Germany, methane emissions from conventional dairy cows compared to organic dairy cows depended greatly on calculation methodology - for example, comparing feed intake vs. taking into account feed quality (Warnecke et al 2014). Emissions from manure were not different between conventional and organic systems. They also found that overall, differences between individual farms were more pronounced than differences between organic and conventional - and emissions are highly dependent on feed quality and manure management.

Fredeen et al. (2013) used chambers to measure enteric methane emissions, comparing feeding a total mixed ration versus pasture forage. They found that the pasture forage resulted in higher quality feed. Milk production was not statistically different in the spring, however in the fall it was slightly lower in the pasture grazing cows, with no difference in enteric methane emissions between the treatments. However, to assess the overall impact of the systems on climate change, the emissions differences between growing grain for a mixed ration compared to managing a perennial pasture should be accounted for.

Reyes-Palomo et al., 2022 found statistically similar carbon footprints (averaging 6.43±21.46 kg CO2eq/kg live weight) in organic and conventional cattle production in an LCA based in the Iberian Peninsula of Spain.

Housing requirements and stocking densities for organic livestock are different from conventional production - however tend to come with the tradeoff of lower yields. Livestock spend more time on pasture - organic ruminants must get most of their forage needs from pasture. Their manure is therefore being deposited on the pasture, almost immediately available to the soil life to incorporate to the soil and feed the pasture plants. When deposited on pasture, manure doesn't need to be stored (manure storage makes up 14% of Canada's agriculture GHG emissions), or transported.

Livestock make a big contribution to organic agriculture via their manure as an amendment. Incentives for organic livestock production could reduce issues with nutrient availability on organic farms, making them more productive and improving the performance of organic GHG emissions intensity. Integrated livestock and field cropping on single farming operations also reduces the need for manure transportation and creates a more cyclical nutrient balance on-farm. These diversified operations present opportunities for other emissions-reducing practices: biogas digesters, manure composting and biochar.

More legumes reduce enteric fermentation emissions - do organic farms feed more legumes?

Within organic farming, are there management opportunities to further reduce GHG emissions from livestock production?

Sources on general GHG emissions from livestock? Stanley et al. 2018; Wittenberg 2005

Conclusion

Agriculture has evolved through history as the foundation that has allowed social development, meeting the food needs of communities while enabling individuals to specialize in disciplines outside of agriculture. However, agriculture has become a business with significant socio-economic contributions. A goal of maximizing production with the support of commercial inputs drives GDP, employment, and economic growth through exports. However, agriculture is not a single purpose manufacturing plant with linear goals of output, efficiency, and economic gain. Agriculture has a large spatial footprint on the planet, and as a result it can have a significant ecological footprint. Organic agriculture strives to minimize this ecological footprint while still being economically viable and supporting needs of society.

The research specifically comparing organic and conventional agriculture and their respective impacts on GHG emissions, GWP, and co-benefits and trade-offs is generally scarce and results can be conflicting. As a model of sustainable agriculture, organic has identified practices that are ecologically grounded while reducing risk, but this has come with the trade-off of reduced gross production per unit land area. Scientific evidence exists from Canada and around the world that there are multiple benefits associated with organic production. However, an abundance of research exists demonstrating that the general principles and specific practices ubiquitous in organic production - diversified rotations, cover cropping, inclusion of legumes, green manures, forages and perennials, etc. - have positive environmental outcomes. However, the analysis is complicated by the diversity of crops, livestock and growing environments that must be considered. It is also difficult to quantify the value of co-benefits of organic such as improved biodiversity, displacement of nitrogen fertilizer manufacture through use of legumes, recycling of nutrient farmer health risk reduction, consumer health risk reduction, freshwater contamination reduction. In contrast yield is easy to quantify and yield increase is a clear, focussed target.

With appropriate research and support, there is still room to improve yield of organic crops through new technologies and further development of ecological solutions such as biocontrols, precision weed management, and recycling of nutrients.

With increased focus on research and participation leading to intergenerational learning from farmers, organic researchers and farmers can strive to narrow the yield gaps between conventional and organic crops. Organic production will continue to be a key strategy for reducing emissions, slowing global warming, preserving soil and water quality, enhancing biodiversity and enhancing climate resilience in the future.

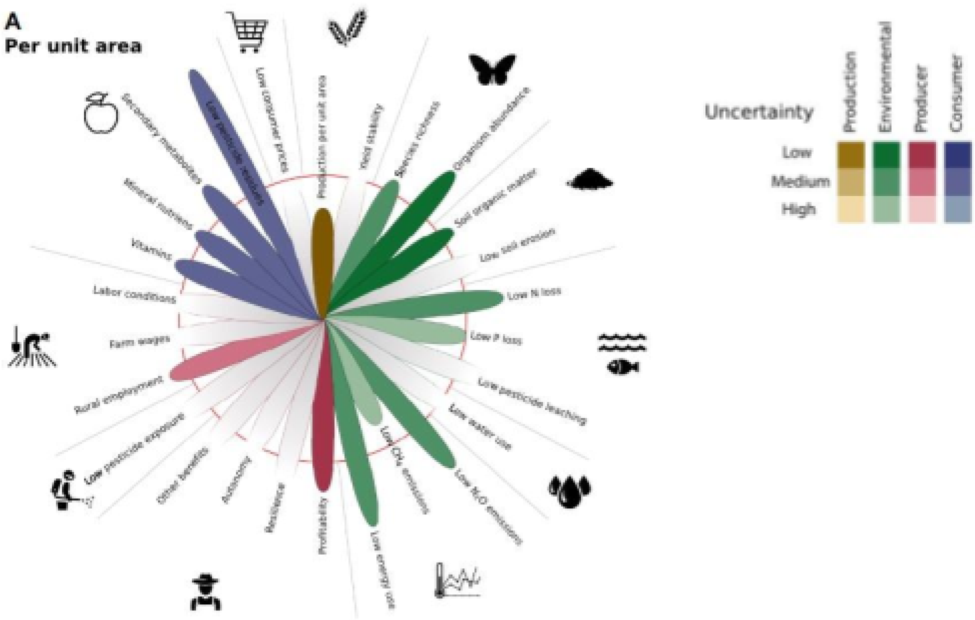

Figure 1. Petal graph from (Seufert & Ramankutty, 2017). The red line represents conventional agriculture's performance and the petals represent organic agriculture's comparative performance.

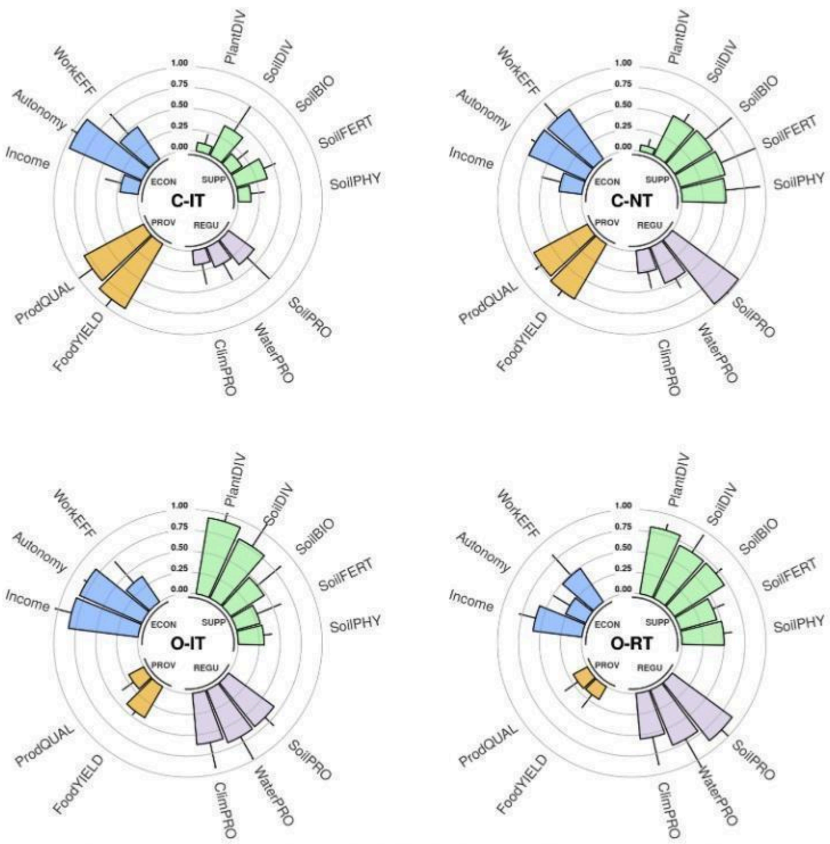

Fig. 2. Standardized agroecosystem function and socioeconomic proxies for the four investigated cropping systems. Mean + 90% confidence intervals, see table S4 for proxy descriptions. Proxies are grouped into SUPPorting (green), REGUlating (purple), PROVisioning (yellow), and ECONomic (blue) categories. The higher the bars, the better the function is performed.

Figure 2. Graphical depiction of the performance of organic and conventional farms. Systems are (clockwise from top left): Conventional intensive tillage, conventional no-till, organic intensive tillage, and organic reduced tillage (Wittwer et al., 2021).

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2.5 Advanced Organic Carbon and Organic Nitrogen Management to Improve Agri-Environmental Outcomes in Canada's Next Agricultural Policy Framework

By: Dr. Derek Lynch

Management Intensity

Gradients of intensity of farm management, including crop rotation diversity (including use of cover crops), nutrient and organic amendment utilization, tillage intensity, and livestock density, exist both across and within all organic cropping and livestock sectors in Canada (Lynch et al 2022; Roberts et al., 2008). This range of management approaches within each organic sector reflects both regional agroecosystem contexts plus variations in approach to organic production systems by individual producers, and directly influences the balance of farm outcomes between productivity and agroecological services with respect to soil organic carbon, soil health and biodiversity. The four case studies highlighted in this report provide an example of such diversity with organic cropping system approaches, from the more intensive short (three-year) crop rotation system and frequent use of green manures at the AAFC Harrow site and which is representative of many commercial organic grain farms in eastern Canada (Lavergne et al, 2025), to the more extensive cropping systems reflected by the Moose Creek Organic Farm site which includes use of perennials and permanent set aside of wetlands on farm.

Advanced Organic Carbon Management

1. **Soil organic carbon (SOC) levels are continuing to decline** particularly across cropping systems in Eastern Canada (Clearwater et al., 2016; Nyiraneza et al. 2017; The Standing Senate Committee on Agriculture and Forestry 2024) leading to declining soil health and soil degradation and loss, due to cropping intensification (less diverse rotations often including low residue crops).
2. Zero-tillage does not reverse SOC declines in humid regions (Angers et al. 2017) and minimum tillage increases N2O emissions on finer textured soils when growing season precipitation exceeds 600mm (Pelster et al., 2024). Thus, SOC gains must be based on added residue and C input to soil.
3. Current federal (OFCAF, Living Labs) and provincial programs are increasing on-farm testing and exploration of **cover crop** utilization. Cover crops have the potential to provide three natural climate solution services; increased SOC, N fertilizer replacement, and reduced N2O emissions and N leaching (Drever et al 2021). However, current cover crop adoption and utilization may not significantly enhance SOC levels, as:
    a. SOC gains from cover crops alone vary widely with their type and utilization (full-season, intercropped, relay cropped etc.) and region. In the prairie region black soil zone average cover crop biomass rates ranges from 0.5 to 0.6 Mg C ha^{-1} yr^{-1} (Thiessen-Martens et al. 2015), but is less in drier prairie regions, compared to up to 2 Mg C ha^{-1} yr^{-1} (~4 Mg biomass) in more humid cropping regions, with earlier planting and later termination achieving upper ranges (Blanco-Canqui, H. 2022). As only a fraction of cover crop soil C input contributes to SOC gain (Gregorich et al 2017), rates of SOC gain, if any, from cover crops are suggested at 0.27–0.39 t C ha^{-1} yr^{-1} or less depending on cover crop biomass production (Poeplau et al, 2024).
    b. Generating higher cover crop biomass rates being avoided due to (i) perceived risk of N immobilization challenges for the following cash crop (R. Barrett pers comm.) (ii) evidence of a link between cover crop biomass and

N2O emissions in humid regions leading to recommendations to use cover crops primarily as a low-biomass catch crop to utilize excess residual soil mineral N (RSMN) (M. Tenuta pers comm; Thapa et al., 2018). Cover crops of low biomass (<2 Mg ha^{-1}), however, are unlikely to contribute to SOC gains (Blanco-Canqui, 2022).
    c. Some studies suggest enhancing SOC levels may not be guaranteed by more diverse rotations which include cover crops unless a period in perennial forages is included (Arcand and Congreves, 2018; Sprunger et al., 2020)

4. Soil is the fundamental and critical non-renewable resource that must be sustained, and SOC is central to all aspects of soil health. While Advanced Nitrogen Management (4 Rs) has a key role to play in achieving GHG reductions in cropping systems, there is a need for a parallel emphasis on **Advanced Carbon Management to sustain SOC, soil health and climate resilience**, i.e. programming geared to enhance testing and adoption, optimized by region, of **4 Rs for carbon**, namely,:
    a. **Rotation** diversification (including cover crops)
    b. **Residue** management (residue exports (straw, hay etc.) can negate gains from diversification)
    c. **Rate** of tillage intensity (based on frequency and level of disturbance/STIR metrics)
    d. **Return** of manure (or composts)

    These **4 Rs for advanced carbon management** are key **features of Regenerative Agriculture** (Newton et al. 2020), and these practices are **routinely utilized in organic cropping systems in varying combinations** depending on intensity of management (Lynch et al. 2022). These 4 Rs are also sometimes known as the 6 Cs, listed by Van Eerd et al. (2021) as: 1. compaction reduction, 2. conservation tillage, 3. crop + animal diversity, 4. continuous living plants, 5. cover crops, and 6. compost + organic amendments.

Advanced Organic Nitrogen Management

Advanced organic N management goes beyond the 4 Rs described by Reetz et al. (2015) as using the right nutrient source, applied at the right rate, at the right time, in the right place.

1. Frequent use of cover crops, as practiced in organic cropping systems, further enhances the significant yield gains from use of cover crops, yield gains in the range of 13-22% shown for corn and wheat in the meta-analysis of Bourgeois et al. (2022). Cover crop mixtures that include legumes may provide yield gains plus increased soil N and C contents (Lavergne et al., 2020).
2. **Current programs and recommendations with respect to improved crediting of organic N sources focus primarily on manure management, with minimal or no emphasis on replacement of N fertilizer use through targeted use of perennial or cover crop legumes in rotation.**
3. Provincial suggested N credits for preceding legume cover crops vary widely and need refinement to enhance fertilizer N replacement and adoption. Outside of organic farming systems, farmer inexperience, and perceived agronomic risks, limit the potential of expanding testing and use of common and novel leguminous cover crops

as predominant source of N supply for the following cash crop. Biological nitrogen fixation (BNF) capacity and soil N supply from some novel leguminous cover crops have been shown in eastern Canada to largely replace N fertilizer needs for corn (Yang et al., 2024), wheat (Alam et al., 2018) and potatoes (Lynch et al., 2012). As with fertilizer N, N from legumes can also lead to N2O emissions (Rochette et al., 2008), but this is offset by cover crop co-benefits to soil health and resiliency, biodiversity, and potential for SOC gain (Lynch, D. H. 2022). Estimates of relative N2O emissions rates from cover crops are also under ongoing revision (Liang et al., 2020). D'Amours et al (2023) in Quebec found that a chisel ploughed green manure minimized per hectare N_2O emissions without increasing crop (barley, corn, soybean) yield-scaled N_2O emissions.

4. The intensity of N fertilizer use has continued to increase across cropping systems in Canada with attendant increases in field scale N balances (N input-outputs). The emission rates of N2O are considered to be non-linear in relation to N inputs and have increased accordingly. Organic farming systems, even within specific sectors, vary in terms of management and farm nutrient intensity (Roberts et al 2008), but are generally significantly less intensive with respect to N flows than conventional cropping systems. As a result, field scale N balances and residual soil mineral N levels post-harvest are typically low in organic cropping systems, with attendant reduced risk of N losses via leaching and direct or indirect N2O losses (Lynch et al 2012).
5. A leguminous, or legumes-in-mixture, perennial or cover crop rotation phase acts as an 'N-buffer' that allows application of diverse carbon-rich soil amendments (composts etc.). Legume BNF ability avoids a loss of biomass productivity due to N immobilization following amendment application (Lynch et al., 2004).

The GHG benefits of advanced organic carbon and organic nitrogen management practices, utilized alone or in-combination, remain understudied and are not currently covered in the NIR. The increasing risk of managing nitrogen in conventional systems at the expense of declining C must be addressed. Organic farming systems are ideal production systems for testing and refinement of Advanced Organic Carbon and Nitrogen Management to Improve Agri-Environmental Outcomes for Canada.

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