Agricultural Greenhouse Gases Indicator

Agri-Environmental Indicators Report

The Environmental Sustainability of Canadian Agriculture

Census Year 2021




Agriculture and Agri-Food Canada
Agriculture et Agroalimentaire Canada
Canada

Agricultural Greenhouse Gases Indicator
Agri-Environmental Indicators Report, Census Year 2021

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Summary

Anthropogenic greenhouse gas (GHG) emissions and their accumulation in the atmosphere are now well established as being the leading cause of global warming and climate change. Compared to the 1951-1980 average, the Earth's mean surface temperature has warmed by about 1.0˚C (GISS, 2023), primarily due to the increase in atmospheric GHG concentrations. Agriculture plays a dual role in climate change, since it is both a source of and a sink for GHGs. While agricultural activities inevitably generate GHGs, which contribute to climate warming, agricultural soils have the capacity to sequester, or store carbon, offsetting the sector's overall contribution. Furthermore, agriculture is dependent on a stable climate in order to realize profitable crop yields. The Agricultural Greenhouse Gas Budget Indicator (also referred to as the Greenhouse Gas Indicator) assesses the state and trend of GHG emissions resulting from Canadian agricultural activities.

The main GHGs emitted from agriculture are nitrous oxide (N_2O) and methane (CH_4), while carbon dioxide (CO_2) can be either emitted or removed (sequestered) as a result of agricultural activities. The Greenhouse Gas Indicator has been used to track the combined N_2O, CH_4 and CO_2 emissions generated by agricultural activities in Canada between 1981 and 2021. Since N_2O, CH_4 and CO_2 have different global warming potentials per molecule, the accepted practice is to report their combined effects in terms of carbon dioxide equivalents (CO_2e).

In 2021, the net GHG emissions (emissions minus removals from soil carbon change) from Canadian agricultural activities, excluding fossil fuel use, amounted to about 36.2 million tonnes of CO_2 equivalents (Mt CO_2e). For all sectors of the Canadian economy, total GHG emissions were 698 Mt CO_2e in 2021, meaning that agriculture accounted for about 5.2% of national emissions. When soil carbon change is omitted from national totals, net GHG emissions were 57.3 Mt CO_2e, about 8.2% of national emissions.

Between 1981 and 2021, net agricultural GHG emissions, including soil carbon change, have declined by 28%, despite greater N_2O, CH_4 and CO_2 emissions, which have increased by 49%, 5% and more than 150% respectively. The fact that the net agricultural GHG emissions have not increased over this period is attributable to the change in CO_2 emissions from agricultural soils, which went from being a carbon source of about 5.4 Mt CO_2e in 1981 to a sink (indicating removal by sequestration) of about 21.0 Mt CO_2e in 2021. Agricultural soils are a significant sink for CO_2, particularly in the Prairie provinces of Canada, owing to the widespread adoption of beneficial management practices (BMPs) such as reduced tillage intensity, decreased

summerfallow and, to a lesser extent, conversion from annual crops to perennial cropping systems.

Furthermore, increasing crop yields over time have led to a greater rate of crop residue return to agricultural soils across Canada. This greater rate of residue return has contributed to a significant increase in the Canadian agricultural soil carbon sink. If soil carbon change is excluded from national totals, emissions have increased by about 27% between 1981 and 2021, from 45.2 to 57.3 Mt CO_2e. In absolute terms, N_2O increased the most between 1981 and 2021 growing from 17.8 Mt CO_2e in 1981 to 26.5 Mt CO_2e in 2021, while smaller absolute increases of 1.4 and 2.0 Mt CO_2e were observed for CH_4 and CO_2 over that same time period.

Between 1981 and 2021, agricultural N_2O emissions increased primarily because nitrogen fertilizer use in Canada has more than doubled. To a lesser extent, increases in livestock populations have also resulted in greater N_2O in addition to CH_4 emissions. However, challenging economic conditions for Canadian livestock producers, particularly those in the beef cattle sector, have led to a reduction in herd size in recent years. As a result, although emissions of CH_4 were still greater in 2021 as compared to 1981, their emissions peaked in 2006 and have been gradually declining since then. Although manure-related N_2O emissions decreased during the same period, the increase in synthetic fertilizer use has more than offset this decline, leading to a net increase in total N_2O emissions between 1981 and 2021. Similar to the increases in emissions linked to nitrogen fertilizers, increased use of carbon-containing fertilizers has increased associated CO_2 emissions.

The issue and why it matters

Greenhouse gases perform an essential role in the atmosphere, trapping radiant energy and maintaining the Earth at a temperature that can support life. Although these gases are essential for the planet, the accumulated anthropogenic emission of these gases in our atmosphere has already impacted the climate and the ongoing addition of GHGs is undesirable, as the resulting increases are likely to bring about major changes in climate. Anthropogenic emissions of carbon dioxide, methane and nitrous oxide have resulted in global atmospheric concentrations that are greater than at any point in the past 800,000 years.

Agricultural activities influence net GHG emissions from a variety of agricultural sources and sinks (Figure 1). Direct N_2O emissions originate primarily from field-applied inorganic and organic fertilizers, crop residue decomposition, and manure storage. Indirect N_2O emissions occur when nitrogen (N) is transported off-site through processes such as volatilization (loss of N to the air as a gas) and the subsequent deposition of ammonia, as well as N leaching and runoff (N dissolved in water). Methane is emitted through enteric fermentation, the process associated with feed digestion in ruminant animals, as well as through the anaerobic decomposition of stored manure. When feed is consumed by livestock, particularly ruminants, microbes that are naturally present in the digestive system decompose the cellulosic material. During this process, some of the feed is converted to CH_4, which is released into the atmosphere when the animals eructate. Similarly, microbial decomposition of manure under anaerobic conditions results in CH_4 emissions.

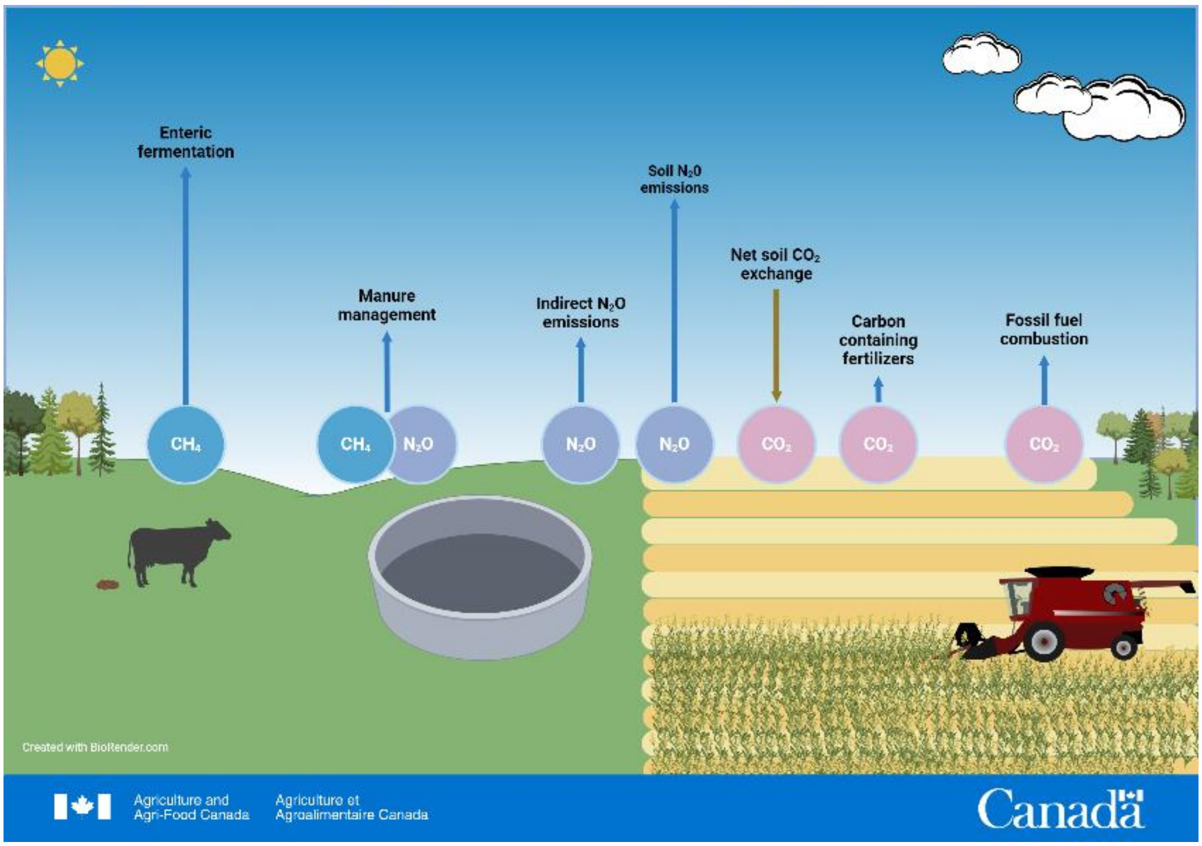

Figure 1: Agricultural GHG emissions in 2021. Arrow length is proportional to the magnitude of the emissions; arrow direction upwards indicates a source and downwards indicates a sink.

Agricultural soils can either be a source or sink of CO_2. The net effect is the difference between CO_2 removal from the atmosphere by growing crops (and subsequent storage in the soil in the form of crop residues and soil organic matter) and its emission to the atmosphere through the decomposition of crop residues and soil organic matter. Management practices that promote the sequestration of carbon in soils tend to increase the amount of residue that is returned to the soil, increase the amount of time during the year that growing vegetation is present on the soil surface, minimize soil disturbance and slow the rate of residue decomposition. Practices that are currently accounted for in calculations include decreasing tillage intensity, reducing the frequency of summerfallow, converting annual crops to perennial crops, the addition of manure to soils, as well as the impact of crop productivity on crop residue return to the soil. There are many other agricultural practices that can contribute to soil carbon sequestration. In this Chapter, we present total GHG emissions both including and excluding soil carbon sequestration, in order to provide consistency with Canada's official GHG inventory (Environment and Climate Change Canada, 2023). For a more detailed explanation of the soil carbon exchange process, refer to the Soil Organic Matter Indicator.

Carbon dioxide emissions are associated with the application of fertilizers containing carbon either from rocks such as limestone and dolomite, as well as from nitrogenous fertilizers containing carbon, such as urea and urea ammonium nitrate. In both cases, the carbon contained in the fertilizer is released as CO_2 after application to cropland. In addition to carbon-containing fertilizers, CO_2 is emitted during fossil fuel combustion by farm machinery and during the manufacture of agricultural fertilizers and machinery (Dyer et al., 2014). Because these emissions of CO_2 are typically reported by the transportation and manufacturing sectors (Environment and Climate Change Canada, 2020; Environment and Climate Change Canada, 2023), they are not included in the Greenhouse Gas Indicator calculations. However, since the emissions are directly associated with decisions that are made on-farm, it is important to assess their magnitude and their evolution over time in order to be able to calculate the carbon intensities associated with various agricultural products (Desjardins et al., 2020).

There are several reasons why developing a national methodology for reporting agricultural GHG emissions is an important area of focus for Canada and for Canadians. The first reason relates to the connection between GHG emissions and climate. Anthropogenic GHG emissions have been conclusively linked to global climate change, and continued emissions are very likely to exacerbate this problem for future generations. Therefore, efforts to decrease net emissions will help mitigate the impacts of climate change. Canada has established a target of reducing national GHG emissions by 40-45% by 2030 relative to 2005 and has committed to achieving net-zero GHG emissions by 2050. The agriculture sector has the potential to work towards this goal by reducing emissions of N_2O, CH_4 and CO_2 and by sequestering carbon in agricultural soils. This can be achieved by either adopting processes or management practices that result in decreased net GHG emissions and by producing bioenergy from agricultural by-products, when this process results in fewer net GHG emissions relative to fossil fuel combustion.

Second, greenhouse gas emissions can be an indication of nutrient losses from agricultural systems, and can therefore be considered a measure of inefficiency and, consequently, an economic loss to the producer. For example, N_2O emissions from fertilizer application do not contribute to crop growth, and livestock feed that is converted into CH_4 represents an energy loss for the animal. On-farm management practices that improve productivity and nutrient-use efficiency can also reduce GHG emissions intensity and improve profitability. However, the full cost of implementing such practices should be taken into account, as the reduction in GHG emissions and associated savings to the producer may only partially offset the investment.

The third reason for concern regarding agricultural GHG emissions relates to marketing and trade. In 2022, the Canadian agri-food sector accounted for $144 billion of gross domestic product, and Canada is the fifth largest agri-food exporter in the world, with a value of nearly $93 billion (Government of Canada, 2023). There is a growing interest in sustainable sourcing among retailers and agricultural supply chains, which may include reporting on, or meeting GHG emissions standards. Some national and multinational corporations have identified the reduction of GHG emissions as a desirable goal, and are developing policies favouring products and services that reduce emissions per unit of production.

Canadian industry groups and companies in the agricultural sector have responded, and are actively working to reduce GHG emissions throughout the value chain. Many have demonstrated leadership by setting ambitious near-term targets for emissions reduction, and some have committed to achieving carbon neutrality by the middle of the century. Developing a science-based methodology to estimate agricultural emissions can help Canadian companies and producers to demonstrate when they have succeeded in reducing their net emissions, and either meet or exceed a GHG emissions standard, enabling market access for these products.

The indicator

The Greenhouse Gas Indicator estimates the net emissions (emissions minus removals) of the three primary GHGs associated with agriculture, specifically CO_2, CH_4 and N_2O. In this version of the Indicator, net GHG emissions are presented both including, and excluding the impact of soil carbon sequestration. Soil carbon sequestration is a large term, that varies substantially year-to-year depending on weather. Favorable weather conditions can result in above average crop yield, and enhance carbon return to the soil, whereas poor weather conditions can result in poor crop yield, decreasing carbon return to the soil. As a result, the inclusion of soil carbon in estimates can obscure long-term trends in other sources of emissions. Therefore, total agricultural emissions are provided in two ways, so that the impact of soil carbon on net emissions can be compared.

International standards, developed by the Intergovernmental Panel on Climate Change (IPCC), require that emissions be reported in carbon dioxide equivalents (CO_2e) using the global warming potential (GWP) of each gas. The GWP accounts for the unique ability of each gas to absorb radiation and for its residence time in the atmosphere. The GWP values used in the IPCC's Fourth Assessment Report (2007), which are the currently accepted values in Canada are as follows: 1 kilogram of N_2O has 298 times the warming impact of 1 kilogram of CO_2, while 1 kilogram of CH_4 has 25 times the impact of 1 kilogram of CO_2. The calculation of CO_2e involves multiplying the mass of N_2O, CH_4 and CO_2 by the factors 298, 25 and 1, respectively. The GWP values are not fixed, but are updated periodically by the international science community as knowledge improves.

Alternate approaches to the GWP have also been proposed, including GWP* (Allen et al., 2018), which is a measure of equivalency in terms of the climate warming that each gas produces, rather than an equivalency of mass for each gas. The GWP* may be more appropriate for agricultural emissions, as it more accurately reflects the impact of gases that have a short lifetime in the atmosphere such as CH_4, especially under stable, or declining rates of emissions (Lynch et al., 2020).

Agricultural CO_2, N_2O and CH_4 emissions are estimated using a globally recognized approach recommended by the IPCC (IPCC, 2006). A Canada-specific IPCC Tier II methodology has been developed by adapting the IPCC framework methodology to account for Canadian conditions, such as climate characteristics, crop management practices, animal production characteristics and animal husbandry techniques that are specific to our country (Environment and Climate Change Canada, 2023; Liang et al., 2020; VanderZaag et al., 2013). There are three main steps in the implementation of the Canadian IPCC Tier II methodology, as follows:

1. Collection of basic input data on climate, crops, livestock and farming systems in Canada, including long-term climate data, the type, area, yield, and rate of nitrogen fertilizer application of each crop, the area associated with specific crop management practices, the population, reproductive status, weight, feed intake, milk production (if applicable) and management practices for livestock and their manure;

2. Estimation of interim variables such as the amount of nitrogen in crop residues, nitrogen excretion by livestock and the gross energy intake of cattle, and calculation of the annual emission factor for one kilogram of nitrogen (for N_2O emissions) or one animal (for CH_4 emissions). The N_2O emission factors are

sensitive to a variety of factors, including climate conditions (average growing season precipitation), the cropping system (annual or perennial), the source of nitrogen (manure, crop residue or synthetic fertilizer), soil texture, and landscape position. Some management practices that are known to affect N_2O emissions including tillage and irrigation practices are also included in the calculations. Individual emission factors for CH_4 emissions from enteric fermentation and manure management have been developed for 52 animal categories. Emission factors to estimate CO_2 emissions from carbon containing fertilizers are constant, and are based on guidance from the IPCC;

3. Calculation of GHG emissions by multiplying the amount of nitrogen (for N_2O emissions), the amount of carbon containing fertilizers (for CO_2 emissions) and the animal population (for CH_4 emissions) by the appropriate emission factor, and then summing the resulting emissions to obtain values at the provincial and national scales.

While the methodology for estimating soil carbon change and CO_2 emissions from cropland employs the same three basic steps as the method for N_2O, CH_4 and CO_2 emissions from carbon containing fertilizers, it differs in that complex computer models are used to develop the emission factors (Smith et al., 2001; Smith et al., 2012). These models estimate the rate of change in soil carbon as a function of local climate, soil type and soil properties and taking into account crop productivity and land management practices that can cause a change in soil carbon levels. These include the frequency of summerfallow and tillage intensity as well as shifts from annual crops to perennial crops. Rates of change are estimated for more than 3,000 geographical regions in Canada. For more information on the calculation of soil carbon change, see the Soil Organic Matter Indicator.

Limitations

Agricultural activities in Canada are carried out on more than 60 million hectares (ha) of land and give rise to many crop and animal products. These products originate from farms ranging in size from a few hectares to several thousand hectares, each with its own unique combination of management practices. Furthermore, soil and climatic conditions vary substantially depending on location. Because of the wide range of crops and animal products, the diversity of management practices, and the variability in soil and climatic conditions, it would be difficult to estimate the Canada-wide agricultural GHG emissions without making certain generalizations to simplify the calculations. For example, when using information at the Soil Landscapes of Canada (SLC) polygon scale as model inputs, the soil type, soil characteristics and climatic conditions were assumed to be uniform within each polygon, and all animals in a specific animal category for a given province were assumed to have the same diet, weight and growth characteristics. These and many other assumptions used in the calculations are sources of uncertainty which affect the accuracy of the emission estimates.

Another source of uncertainty relates to the scientific field measurements that are required to derive Canada-specific emission factors. Field measurements of greenhouse gas emissions are usually limited to a very specific time and place; however, in calculating the Greenhouse Gas Indicator, these were generally applied to a much broader geographic area and to a much longer time frame. Occasionally, it is necessary to use coefficients or emission factors that are not based on Canadian field measurements, but are instead obtained from international research. These add uncertainty to the estimates due to the unknown nature of their applicability to Canada.

There is an additional challenge as the agricultural sector is very dynamic, and producers are continuously looking to bring new products to market, and to adopt practices that improve productivity and profitability and reduce environmental impacts. Changes to agricultural management have the potential to alter GHG emissions, and as new management practices become common with producers, the science required to understand their impact on emissions will lag behind, as it takes time to study the new management and determine if it alters emissions. Furthermore, adoption of new management practices may require input data that was previously not collected in order to account for the impacts on GHG emissions. As a result, the science of estimating agricultural GHG emissions is continuously trying to catch up, looking to understand and model the changing nature of Canadian agriculture.

For example, there has been significant interest in recent years regarding the potential for management practices to improve on-farm nitrogen use efficiency, and as a consequence, contribute to reduced N_2O emissions from synthetic fertilizers. These practices include the use of Enhanced Efficiency Fertilizers (EEF), the timing of fertilizer application, the placement of fertilizer and the rate at which fertilizer is applied. Currently, data is being collected as a part of field measurements to quantify the magnitude of impact on emissions associated with these practices, as well as to determine the rate of adoption of these practices by Canadian producers. Once these data are obtained, they can be implemented in future versions of the GHG Indicator for Agriculture. It should also be noted that while the models used are robust, due to limitations in the understanding of processes that control GHG emissions, it is not possible to account for all factors in the calculations that affect emissions.

Last, substantial changes in the methodology to estimate agricultural emissions have been implemented in the Greenhouse Gas Indicator in recent years. These changes, based on the latest scientific knowledge, result in significantly different estimates of soil carbon sequestration and agricultural N_2O emissions. As a result, GHG emissions estimates published in previous versions of the Greenhouse Gas Indicator will differ from and are not directly comparable to estimates presented here.

Results and interpretation

Net Canadian agricultural emissions decreased between 1981 and 2021, by 14.4 Mt CO_2e (Table 1), when soil carbon sequestration is included. The significant reduction in net agricultural GHG emissions over this time period is primarily attributable to the change in soil carbon, which went from being a source (5.4 Mt CO_2e) in 1981 to a sink of about -21.0 Mt CO_2e in 2021. This increase in soil carbon sequestration more than offset the 49% increase in agricultural N_2O emissions (from 17.8 to 26.5 Mt CO_2e), the 5% increase in agricultural CH_4 emissions (from 26.2 to 27.6 Mt CO_2e) and the 159% increase in CO_2 emissions (from 1.2 to 3.2 Mt CO_2e). However, if soil carbon sequestration is excluded from national totals, net GHG emissions have increased by 27% from 45 to 57 Mt CO_2e between 1981 and 2021.

This highlights the importance of soil carbon in our net GHG emissions, as the inclusion or exclusion of these emissions changes the trend in emissions between 1981 and 2021 from decreasing to increasing. Soil carbon change also depends significantly on crop productivity, and therefore on weather. As a result, soil carbon sequestration can be variable from year to year. Favourable weather conditions in some years can substantially increase crop productivity and positively contribute to soil carbon. But the opposite is also true: poor weather conditions can lead to low productivity, negatively impacting soil carbon sequestration. Despite the possibility of short-term weather conditions which result in a net release of CO_2, Canadian agricultural soils are estimated to have been a significant sink for CO_2 since 1981.

Figure 2 shows the trend for N_2O, CH_4, CO_2, and soil CO_2 individually as well as collectively in terms of net GHG emissions in the Prairie provinces (Alberta, Manitoba and Saskatchewan) between 1981 and 2021 (data for this graph can be referenced in Table 1). Again, the importance of soil carbon is shown, as the net emissions in 2021 for the Prairie provinces were 13 Mt CO_2e when the change in soil carbon is included, but are much larger at 37 Mt CO_2e when these emissions are excluded. The trends in the emissions of the three GHGs are due to different factors. For instance, the 73% increase in agricultural N_2O emissions is primarily attributable to increases in nitrogen fertilizer application. National nitrogen fertilizer use, which stood at about 0.94 million tonnes of nitrogen in 1981, has more than doubled, reaching 3.0 million tonnes in 2021 (Figure 3).

The increase in nitrogen fertilizer use is not evenly distributed across the country, as use in Western Canada increased by nearly 300%, whereas use in Eastern Canada increased by only 64%. While the dramatic increase in nitrogen fertilizer use has boosted crop yields, N_2O emissions have increased as well. Other factors have also contributed to the upward trend in agricultural N_2O emissions since 1981, albeit to a lesser extent: the greater crop residue nitrogen associated with increased crop production, the increase in manure nitrogen excretion associated with the expanded overall livestock population and the general increase in animal size.

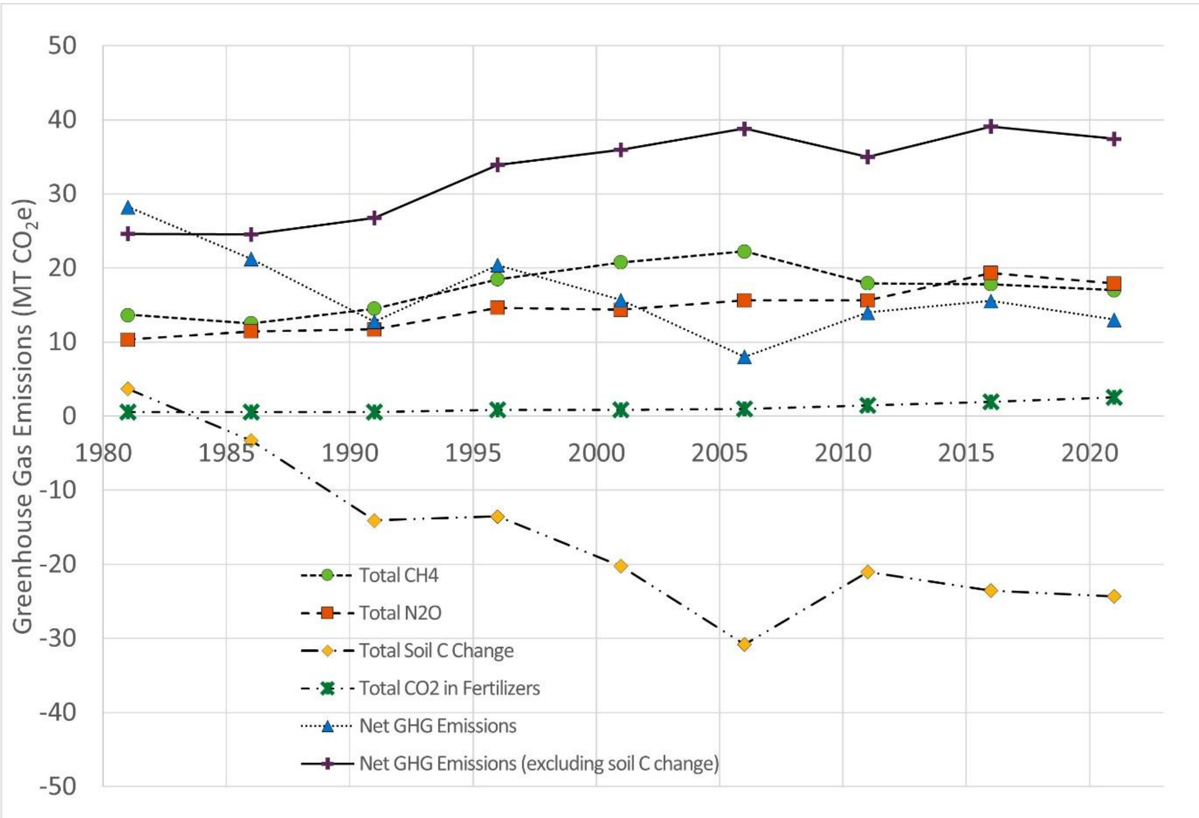

Figure 2: Agricultural greenhouse gas emissions in the Canadian Prairies (Alberta, Manitoba and Saskatchewan, collectively), 1981-2021

Table 1: Canadian agricultural GHG emissions (Mt CO_2e), 1981 to 2021. Note that totals may differ slightly due to rounding. (*Note: formatted for a tabloid layout*).

	N_2O									CH_4									CO_2									Soil C									Total								
	1981	1986	1991	1996	2001	2006	2011	2016	2021	1981	1986	1991	1996	2001	2006	2011	2016	2021	1981	1986	1991	1996	2001	2006	2011	2016	2021	1981	1986	1991	1996	2001	2006	2011	2016	2021	1981	1986	1991	1996	2001	2006	2011	2016	2021
BC	0.77	0.72	0.72	0.81	0.85	0.78	0.77	0.81	0.85	1.57	1.42	1.53	1.76	1.84	1.82	1.44	1.61	1.73	0.03	0.03	0.02	0.03	0.03	0.02	0.02	0.03	0.04	-0.12	0.06	-0.04	-0.25	-0.17	-0.21	0.01	-0.17	0.13	2.25	2.23	2.24	2.34	2.56	2.41	2.25	2.27	2.75
AB	5.06	5.18	5.55	6.58	6.74	7.06	7.37	8.25	7.36	7.66	7.21	8.70	10.84	12.35	12.15	9.97	10.12	9.46	0.25	0.25	0.23	0.30	0.34	0.39	0.63	0.73	0.92	-0.08	0.29	-1.24	-5.53	-3.55	-10.52	-10.22	-3.69	-4.74	12.89	12.93	13.25	12.19	15.87	9.08	7.75	15.41	13.01
SK	2.39	2.96	2.70	3.95	3.74	4.12	4.59	6.06	5.73	3.88	3.22	3.67	4.87	5.28	6.43	5.11	4.93	4.99	0.19	0.19	0.17	0.37	0.35	0.43	0.60	0.94	1.21	2.14	-1.39	-8.92	-6.72	-12.48	-21.59	-9.42	-15.78	-15.43	8.60	4.98	-2.38	2.47	-3.11	-10.61	0.89	-3.86	-3.49
MB	2.87	3.31	3.47	4.08	3.89	4.43	3.65	5.01	4.79	2.14	2.06	2.15	2.78	3.10	3.67	2.85	2.77	2.56	0.13	0.13	0.14	0.16	0.17	0.18	0.22	0.28	0.39	1.63	-2.21	-3.88	-1.30	-4.22	1.26	-1.38	-4.07	-4.19	6.77	3.29	1.88	5.72	2.94	9.54	5.34	3.99	3.55
ON	4.02	3.80	3.42	3.44	3.46	3.44	3.48	3.65	4.06	5.92	5.22	5.09	5.31	5.07	4.94	4.30	4.26	4.37	0.27	0.27	0.24	0.26	0.17	0.20	0.20	0.20	0.25	1.44	0.79	1.39	1.25	2.51	1.26	1.12	1.88	1.52	11.64	10.08	10.13	10.26	11.22	9.83	9.10	10.00	10.19
QC	2.14	2.27	2.25	2.37	2.70	2.17	2.44	2.99	3.08	4.33	3.91	3.74	4.03	4.01	4.15	3.92	3.82	3.95	0.26	0.26	0.26	0.26	0.24	0.18	0.21	0.26	0.25	0.32	0.14	0.45	0.71	1.94	1.07	0.97	1.04	1.45	7.05	6.58	6.68	7.38	8.89	7.58	7.54	8.11	8.73
NB	0.22	0.23	0.22	0.24	0.25	0.25	0.21	0.23	0.27	0.23	0.23	0.22	0.21	0.23	0.22	0.20	0.17	0.16	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	-0.01	-0.01	0.01	0.03	0.03	0.03	0.03	0.05	0.11	0.51	0.52	0.52	0.56	0.59	0.57	0.51	0.52	0.62
NS	0.16	0.16	0.15	0.16	0.15	0.14	0.12	0.13	0.14	0.29	0.28	0.27	0.28	0.27	0.26	0.22	0.21	0.20	0.04	0.04	0.04	0.04	0.03	0.01	0.01	0.02	0.02	-0.02	0.03	0.05	0.04	0.06	0.04	0.06	0.05	0.06	0.47	0.51	0.51	0.51	0.50	0.45	0.41	0.40	0.43
PE	0.12	0.12	0.12	0.14	0.13	0.13	0.10	0.13	0.16	0.18	0.17	0.16	0.17	0.16	0.16	0.13	0.12	0.14	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.07	0.04	0.06	0.08	0.05	0.03	0.05	0.04	0.02	0.37	0.34	0.35	0.39	0.35	0.34	0.28	0.30	0.33
NF	0.02	0.02	0.03	0.03	0.02	0.03	0.02	0.02	0.04	0.02	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.06	0.07	0.07	0.07	0.09	0.10	0.10	0.12
CAN	**17.77**	**18.78**	**18.63**	**21.81**	**21.93**	**22.56**	**22.76**	**27.29**	**26.48**	**26.23**	**23.75**	**25.55**	**30.27**	**32.35**	**33.85**	**28.18**	**28.06**	**27.60**	**1.23**	**1.23**	**1.18**	**1.49**	**1.41**	**1.49**	**2.00**	**2.54**	**3.20**	**5.37**	**-2.23**	**-12.11**	**-11.69**	**-15.81**	**-28.61**	**-18.76**	**-20.64**	**-21.05**	**50.60**	**41.52**	**33.25**	**41.89**	**39.88**	**29.29**	**34.17**	**37.25**	**36.23**

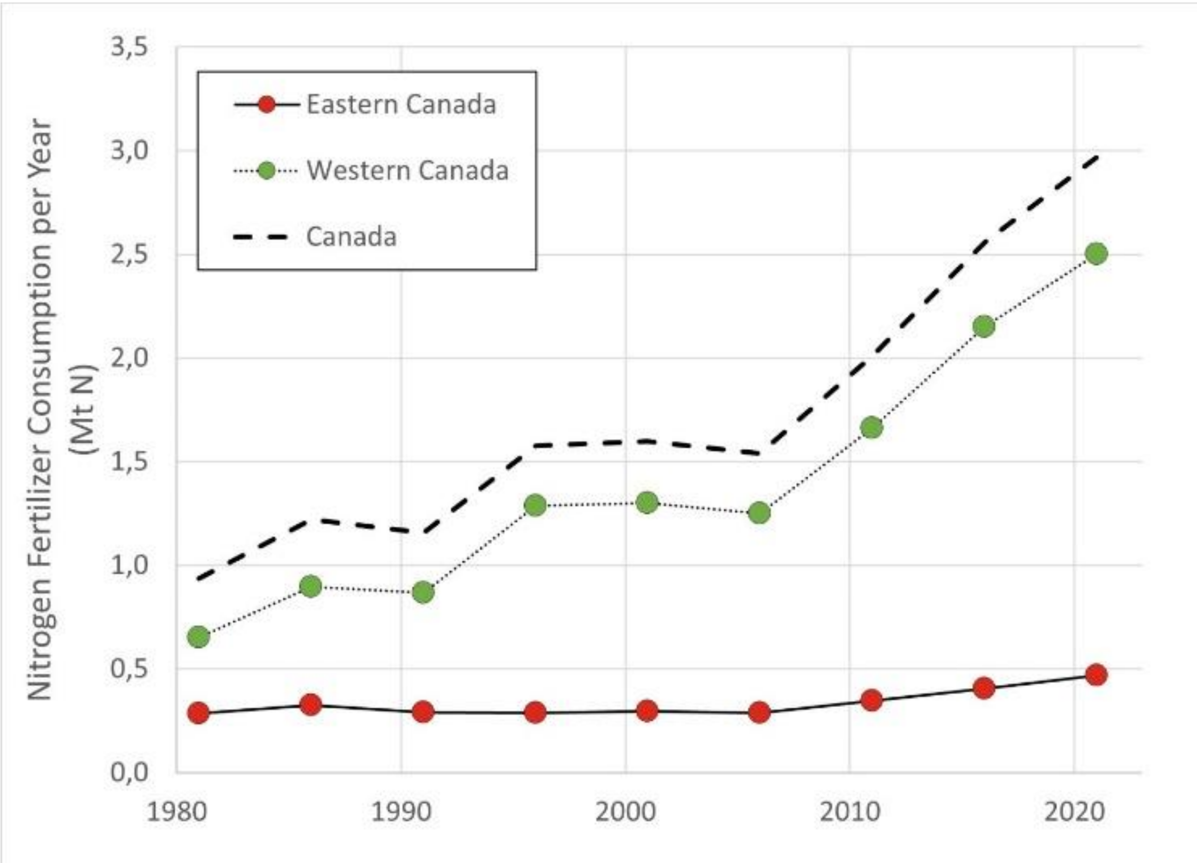

Figure 3: Nitrogen fertilizer use in Eastern and Western Canada, 1981-2021

In contrast, agricultural CH_4 emissions in Canada increased by only 5% between 1981 and 2021. After peaking in 2006, agricultural CH_4 emissions have decreased significantly. This change in emissions is primarily attributable to fluctuations in the livestock population, with CH_4 emissions from enteric fermentation, primarily by beef and dairy cattle, accounting for 89% of total agricultural CH_4 emissions; the remainder is attributable to manure management. Between 1981 and 2021, Canada's dairy cow population experienced a steady decline from about 1.8 million to 1.0 million head (Figure 4) due to an associated increase in milk production per dairy cow. These productivity gains have allowed total milk production in Canada to remain relatively constant while permitting a reduction in the overall dairy cow population.

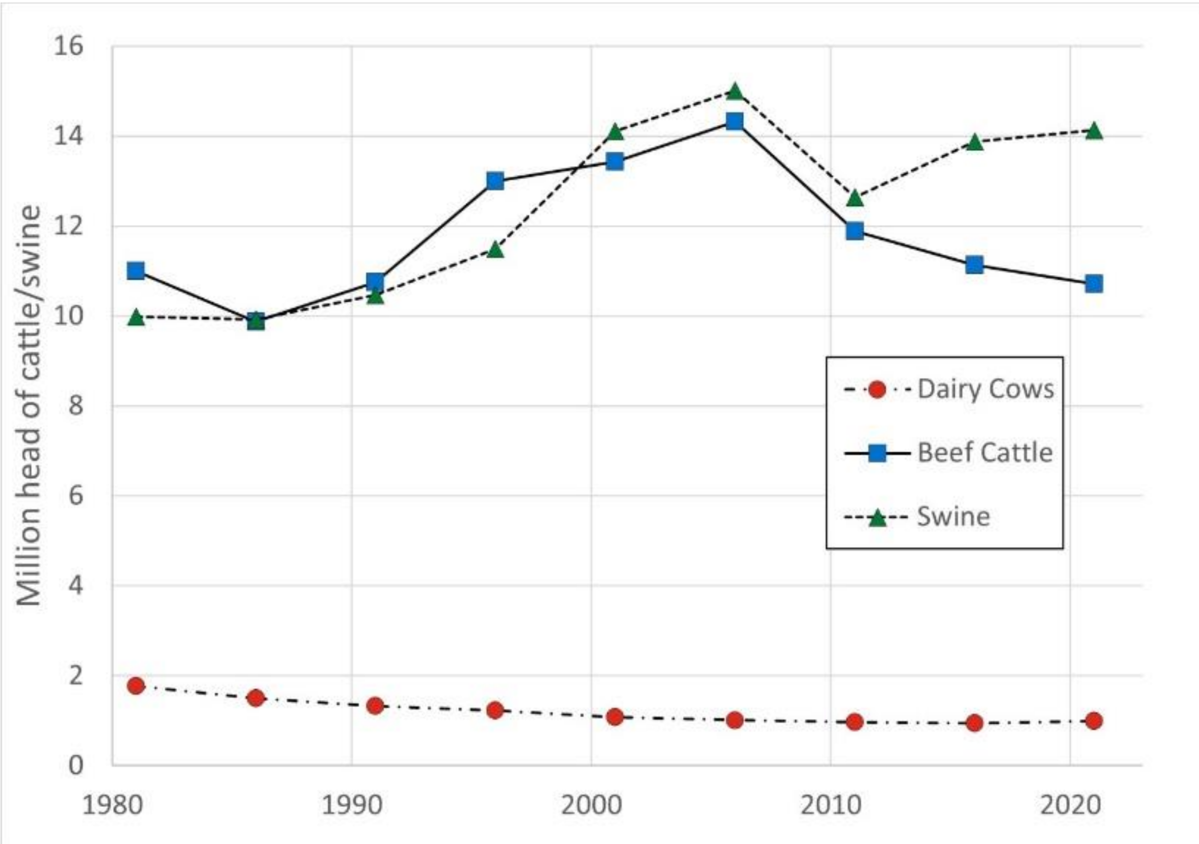

Figure 4: Cattle and swine population in Canada, 1981-2021

The beef cattle population in Canada followed a different trend, increasing between 1986 and 2006, then decreasing between 2006 and 2021. The recent decline in the beef cattle population has a variety of causes, including holdover effects from the bovine spongiform encephalopathy (BSE) crisis in 2003-2004; a high Canadian dollar which has made exports to the United States more expensive; higher domestic costs (e.g. land, feed, labour); decreasing per-capita consumption of beef; and country-of-origin labelling which could discourage consumers in other nations from consuming Canadian beef. These factors, among others, have combined to create a challenging economic environment for Canadian cattle producers and have resulted in a decline of greater than 3.5 million head (about 25%) in the beef population between 2006 and 2021. Primarily as a result of declining cattle numbers, Canada's agricultural CH_4 emissions decreased between 2006 and 2021, and are now only 5% higher than they were in 1981. However, per head cattle emissions have increased over time, as the animals now tend to consume more feed, are more productive, produce more manure and are larger than their counterparts in 1981. The trend toward larger animal size has partially offset the recent decline in livestock-based greenhouse gas emissions associated with reduced cattle herd size.

Swine are not as important a direct source of CH_4 emissions as cattle because they do not produce significant CH_4 emissions from enteric fermentation. However, liquid manure management systems predominate in the swine industry, and they are a major source of CH_4 emissions due to the anaerobic decomposition of the organic material in the stored liquid manure. The swine population has increased by 42% since 1981; however, challenging market conditions and the Cull Breeding Swine Program in 2008 led to a decrease in total swine population between 2006 and 2011, from which the sector is still recovering.

Changes in agricultural land management practices and increased crop productivity have been the primary factors behind the increase in soil carbon sequestration. Crop management practices that minimize soil disturbance, such as reducing summerfallow, decreasing tillage intensity and increasing perennial cropping, can enhance carbon sequestration in the soil. Furthermore, a general increase in crop yield (i.e. amount of crop produced per unit of land) has contributed to greater residue to the soil, and greater carbon sequestration.

Between 1981 and 2021, there was a significant increase in the land area on which these beneficial crop management practices were carried out. For instance, the area devoted to summerfallow has declined from 9.7 million ha to less than 0.5 million ha, and the area under no-tillage has increased from 0.6 million ha to 19.9 million ha. A reduction in the area of summerfallow has increased crop production and decreased the amount of bare soil, while the adoption of minimum till and no-till practices limits soil disturbance by reducing the need to use machinery to turn the soil. As a result, an increased amount of residue is returned to the soil, decomposition of organic material slows, and more carbon accumulates. Although the area dedicated to perennial forage crops increased from 5.8 million ha to 7.9 million ha between 1981 and 2006, recent declines in the beef and dairy herd have reduced overall feed requirements and the need for perennial forages. As a result, the total area of perennial forages is currently declining and in 2021 occupied a smaller area as compared to 1981.

Carbon dioxide emissions from the decomposition of carbon-containing fertilizers and soil amendments are counted as sources of GHGs. Some nitrogen-containing fertilizers such as urea ammonium nitrate and urea, as well as soil amendments such as limestone and dolomite, applied to land reduce soil acidity, release CO_2 after field application. Use of these types of fertilizers and soil amendments has increased between 1981 and 2021, and as a result the associated GHG emissions have more than doubled from 1.2 to 3.2 Mt CO_2e.

The net agricultural GHG emissions, including soil carbon change, per hectare of farmland area at the scale of SLC polygons for 2021 are generally lower per hectare in Western Canada than in Eastern Canada (Figure 5). There are many reasons for this difference. For instance, in the Prairie provinces, soil and climatic conditions are favourable for the adoption of land management practices that can enhance carbon sequestration in the soil. Furthermore, favourable weather conditions across much of Western Canada during the 2021 growing season led to above-average crop production and crop residue return to the soil, which promotes soil carbon sequestration.

In contrast to Western Canada, wetter conditions in Eastern Canada are favourable for the formation of N_2O; the rate of N_2O emissions is often twice as high as in Western Canada. Since water is less of a limiting factor for crop growth in Eastern Canada, high-yielding crops such as corn, which require greater inputs of nitrogen fertilizer, are widely grown there. Eastern Canada is also home to the majority of our dairy herd, which has declined in total size between 1981 and 2021. As the size of the dairy herd has declined over time, a corresponding decrease in perennial forage crops has occurred. When these perennial crops are converted to annual crops, soil C is lost, tending to increase the total GHG emission per hectare.

Furthermore, in Eastern Canada, there is less land area for agriculture, a situation that has resulted in a concentration of farming activities and an increase in GHG emissions per hectare. Despite this, there are some areas of Western Canada where emissions per hectare can be as high as in Eastern Canada. These areas tend to have large concentrations of either beef cattle or swine, or tend to be associated with the more humid black soil zone, where N_2O emissions are greater.

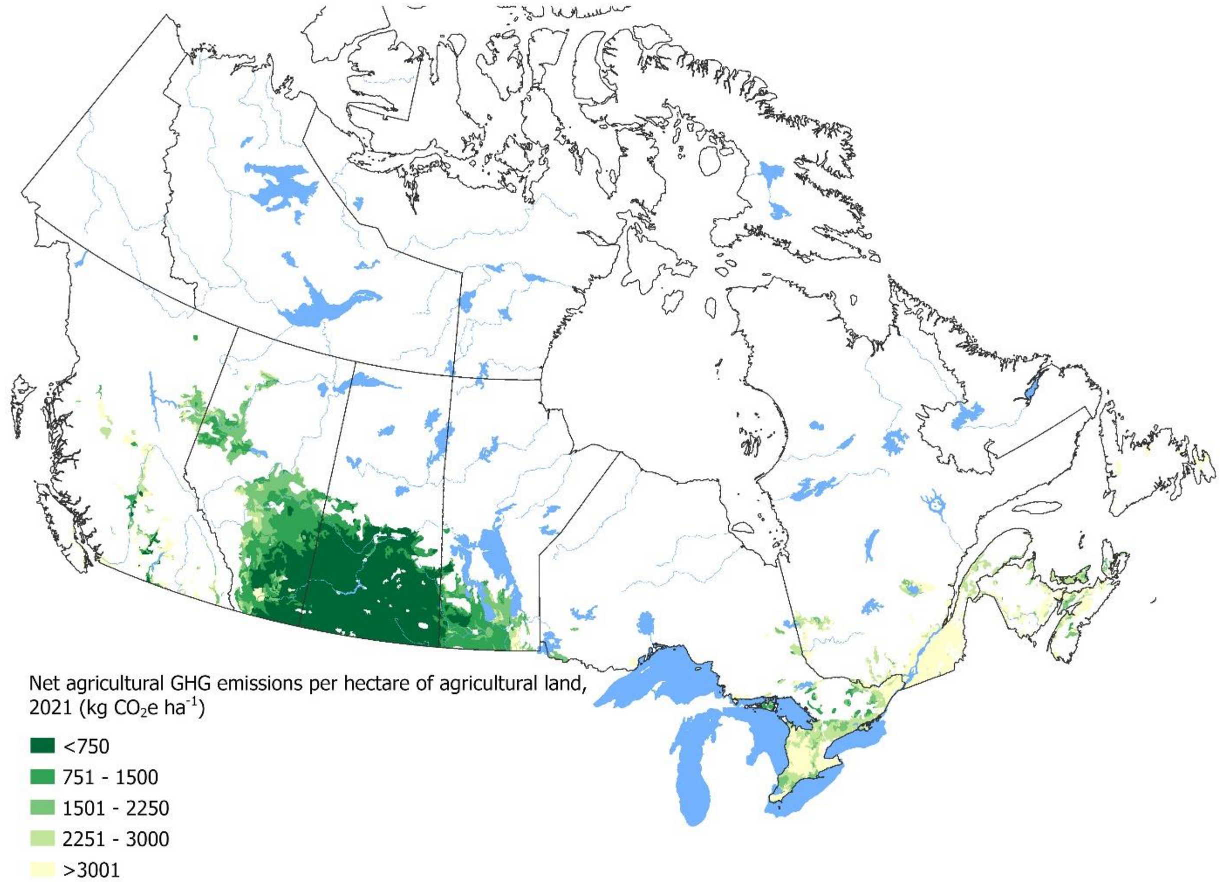

Figure 5: Net agricultural GHG emissions per hectare of agricultural land, 2021 (kg CO_2e ha^{-1})

Figure 6 shows the change in net agricultural GHG emissions between 1981 and 2021 in kilograms per hectare of agricultural area at the SLC scale. Negative values indicate that net emissions have declined over this time period, whereas positive values indicate that net emissions have increased. Large areas of Saskatchewan and Alberta saw either no change or a decline in net GHG emissions, primarily as a result of soil carbon sequestration. These areas are typically drier regions where crop production predominates over livestock production and significant adoption of management practices that sequester carbon has occurred. However, certain areas of Alberta, Saskatchewan and Manitoba experienced an increase in net agricultural GHG emissions, mainly due to the expansion of the animal population between 1981 and 2006, as well as an increase in nitrogen fertilizer use between 1981 and 2016.

In Eastern Canada, large areas in southwestern Ontario, the St. Lawrence River Valley and the St. John River Valley have had a net increase in agricultural GHG emissions as a result of an expansion in annual cropping and an increase in land area dedicated to crops with a high N-demand, such as corn. Declining dairy herds in these regions have led to a decreased need for perennial forage crops and a consequent conversion to annual crops, resulting in higher soil CO_2 emissions and greater N_2O emissions due to elevated nitrogen fertilizer requirements.

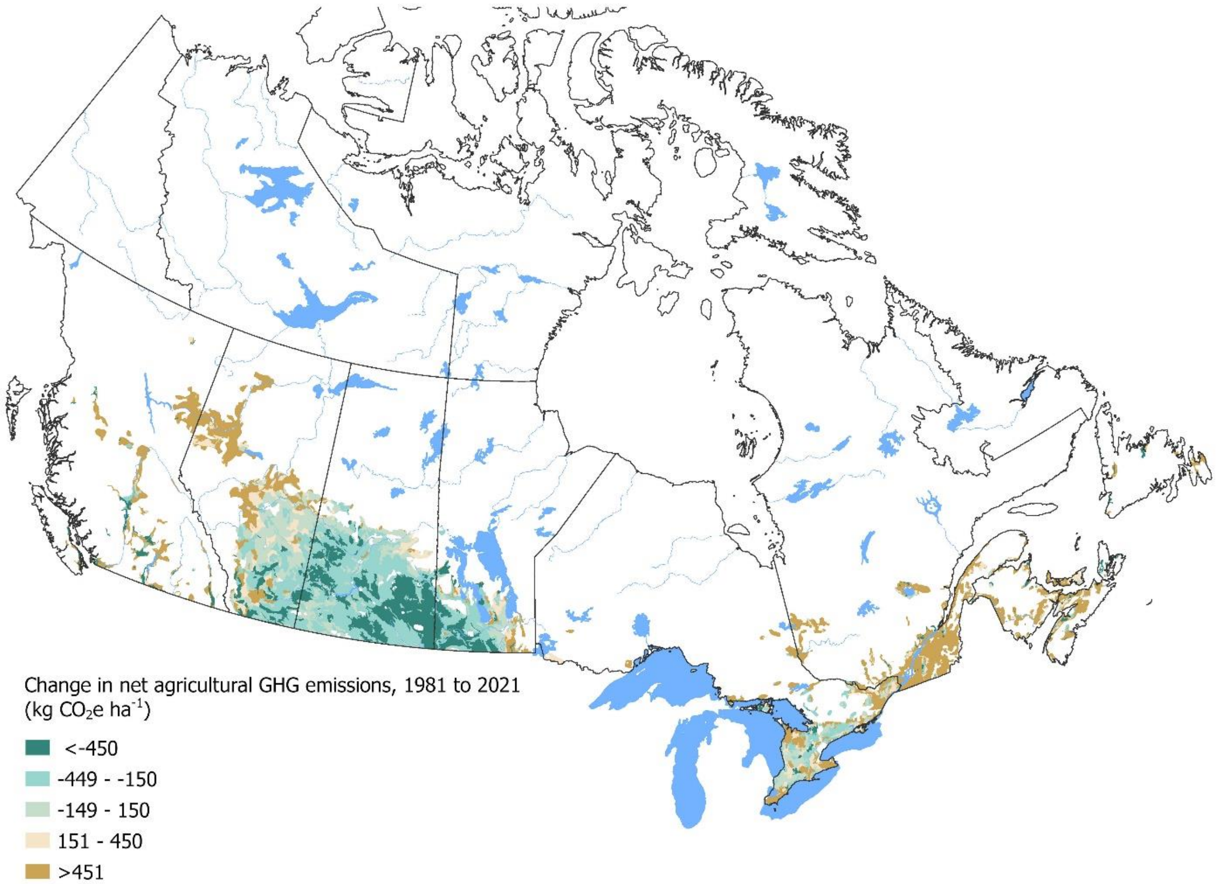

Figure 6: Change in net agricultural GHG emissions, 1981 to 2021 (kg CO_2e ha^{-1})

Response options

The goal of the Canadian agricultural sector is to provide a sustainable source of safe and nutritious food for consumers, while maintaining profitability for the producer. As the Canadian and global population expands, and as global affluence increases along with the trend towards higher protein diets, the demand for Canadian agricultural products is likely to increase. A certain level of N_2O and CH_4 emissions will always be associated with farming activities. Therefore, if agricultural production continues to grow in the future, without significant adoption of mitigation measures, there is a strong likelihood that N_2O and CH_4 emissions from Canada's agriculture sector will also increase. However, there are many options for the mitigation of agricultural GHG emissions, including the following:

- Ruminant diet supplementation with either edible oils, other feed alternatives or additives to reduce CH_4 emissions from enteric fermentation;
- Improved manure management practices or treatments to reduce emissions and to produce bioenergy;
- Management of pastures for intensive short-duration grazing periods, followed by long recovery periods to maximize grass regrowth, promote residue return, and carbon sequestration.
- Adoption of nitrogen fertilizer management practices, such as the timing, placement and rate of application, as well as selecting specific fertilizer products that optimize nitrogen use efficiency and can simultaneously reduce N_2O emissions;
- Increased production of pulses and other legumes, which require less nitrogen fertilizer due to their ability to fix nitrogen;
- Adoption of management practices such as decreased use of summerfallow, reduced tillage intensity and increased perennial cropping to increase carbon storage in agricultural soils;
- Increased use of cover cropping and intercropping maximizes the duration and extent of vegetative cover of the soil and increases the amount of residue returned to the soil;
- Silvopastures (woodlands managed for grazing), can provide additional land for agricultural use while increasing productivity and carbon sequestration. Development of silvopastures could also potentially contribute to Canada's commitment to plant 2 billion trees by 2030.

Many of these agricultural GHG mitigation practices fall into a suite of Natural Climate Solutions (NCS) that can contribute to reducing net emissions in Canada (Drever et al., 2021). Typically, NCS practices not only offer the potential to reduce GHG emissions, but have additional advantages in providing other environmental co-benefits such as improved air, water and quality, and enhanced biodiversity.

There are additional practices to mitigate GHG emissions that depend on, but will not reduce emissions from the agricultural sector. For instance, the production of biofuels from agricultural by-products (e.g. crop residues) will reduce emissions from the transportation sector by reducing consumption of fossil fuels, but are unlikely to impact emissions from the agricultural sector. However, adoption of such practices should consider the impact of long-term diversion of organic material on soil health and avoid soil carbon sequestration.

In general, the adoption of many mitigation practices is hindered to some extent by current economic, regulatory, cultural, technological and/or physical factors. Here are some examples.

- Alternative feed products and diet supplementation for livestock is rarely justified for strictly economic reasons;
- Production of green energy from manure management is often limited, owing to technological, financial and regulatory constraints;
- The level of pulse and legume production is dictated by demand, which is partly dependent upon cultural and dietary preferences;
- Soils have a finite capacity to store carbon and, over time, will approach their maximum sequestration capacity;
- Adoption of some management practices may be hindered by existing machinery, cultural practices and time constraints.

The need for increased food production to satisfy growing global demand and the limitations of existing mitigation measures for agricultural GHG emissions mean that achieving sizeable reductions in net agricultural GHG emissions is a significant challenge. Emission intensity is a measure of the amount of greenhouse gas emitted per unit of agricultural commodity produced, such as a litre of milk, or a kilogram of beef (Desjardins et al., 2020; Dyer et al., 2010). When agricultural products are compared on an equivalent basis, for instance, per kilogram of protein, they differ substantially in their carbon footprint (Dyer et al., 2010).

Therefore, consumers have a significant role to play in reducing emissions from the agricultural sector (Dyer et al., 2020), as with increased knowledge, consumers can make informed decisions regarding the amount of GHG emissions associated with their food choices. However, changes to the consumption of agricultural products by Canadians do not necessarily mean that agricultural GHG emissions will be reduced in Canada. This is because Canada’s agricultural sector is significantly export-based, meaning that a domestic shift to low-carbon agricultural products could be offset by increased international demand for higher-carbon products. Opportunities exist for producers to continue reducing emission intensity through the adoption of increasingly efficient management strategies; however, total emissions may nonetheless increase due to an overall increase in production.

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