Agricultural Greenhouse Gas Emissions in Canada: A New, Comprehensive Assessment

Second Edition: Updated to include 2020 emissions values and revised ECCC methodologies

National Farmers Union
June 2022

For a summary of changes between the First and Second Editions, please see the preface and Appendix A

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The NFU wishes to thank its many members, officials, and staff who contributed to the creation and refinement of this report. The NFU would also like to thank those who peer-reviewed the First Edition of this document: experts in GHG emission measurement and reporting, including current and former staff from Agriculture and Agri-Food Canada (AAFC) and Environment and Climate Change Canada (ECCC) as well as academics and other experts. We gratefully acknowledge the assistance of ECCC in providing data. This report would not have been possible without the work and cooperation of government agencies.

Suggested citation: Darrin Qualman and National Farmers Union, *Agricultural Greenhouse Gas Emissions in Canada: A New, Comprehensive Assessment*, Second Edition (Saskatoon: NFU, June 2022).

For more NFU analysis and an exploration of emission-reduction solutions, please see:

Tackling the Farm Crisis and the Climate Crisis, 2019, and

Imagine If.... A Vision of a Near-Zero-Emission Farm and Food System for Canada, 2021.

Both are available at www.nfu.ca

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Preface to the Second Edition

The NFU completed the First Edition of this report in March 2022. In April, as expected, Environment and Climate Change Canada (ECCC) released its annual *National Inventory Report* (NIR), which included data on GHG emissions and fluxes for 2020. Most critically, *NIR 2022* included very significant changes in the methodologies for calculating nitrous oxide (N_2O) emissions from synthetic fertilizer and manure and also in the methodologies for calculating carbon/CO_2 fluxes between the atmosphere and soils—also known as "sequestration." These very significant changes in methodologies led to equally large changes in the values for these emissions and fluxes, such that the main graph in this Second Edition (see Figure 3, below) looks much different than the main graph from the First Edition (See Figure 6, below).

Compared to *NIR 2021*, in *NIR 2022*, N_2O emissions from synthetic nitrogen fertilizer have been reduced by approximately 20 percent in all years, i.e., from 1990 to 2020 (see *NIR 2022*, Table 5–8[1]). And N_2O emissions from the application of organic nitrogen fertilizers (incl. manure) and decomposition of crop residues have been reduced by about 40 percent. On the other side, fluxes of carbon/CO_2 from the atmosphere to soils, aka "sequestration," have been increased by 100 to 400 percent, depending on the year, as ECCC adopted a new methodology based on crop residue carbon inputs.

For details on all differences between the First Edition of this report and this Second Edition, please see Appendix A, at the end of this report.

Introduction to the First Edition

This report presents, for the first time, a single detailed picture of nearly all sources of greenhouse gas (GHG) emissions from Canadian agricultural production and production of associated farm inputs. See Figure 3. This comprehensive, fine-grained picture of agricultural emissions is crucial to farmers' and policymakers' efforts to reduce those emissions. With adequate policy and program support and a clear understanding of GHG sources, farmers can make a large contribution to Canada's success both in meeting its international emission-reduction commitments and also in helping stabilize the climate.

Canada has committed to reduce economy-wide GHG emissions by at least 40 percent by 2030 and to reach net zero by 2050. Specific to agriculture, the federal government has committed to work with farmers and industry to reduce emissions from fertilizer use to 30 percent below 2020 levels by 2030[2] and to reduce methane emissions from livestock production as part of Canada's larger pledge to reduce *overall* methane emissions to 75 percent below 2012 levels by 2030.[3] Big changes are coming, fast, for every sector of the Canadian economy, including farming.

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[1] "National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada," Part 1, Canada's Submission to the United Nations Framework Convention on Climate Change (UNFCC) (Ottawa: ECCC, April 2022).

[2] Environment and Climate Change Canada, "A Healthy Environment and a Healthy Economy: Canada's Strengthened Climate Plan to Create Jobs and Support People, Communities and the Planet" (Ottawa: ECCC, December 2020), https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/healthy_environment_healthy_economy_plan.pdf.

[3] Environment and Climate Change Canada, "Canada to Launch Consultations on New Climate Commitments This Month, Establish Emissions Reduction Plan by the End of March 2022," news releases, December 3, 2021, https://www.canada.ca/en/environment-climate-change/news/2021/12/canada-to-launch-consultations-on-new-climate-commitments-this-month-establish-emissions-reduction-plan-by-the-end-of-march-2022.html.

To properly plan and implement the many on-farm changes needed to achieve emissions reductions and to design and fund the government programs needed to accelerate and *support* those on-farm changes, farmers and policymakers need to understand emissions: we need detailed, comprehensive numbers. In almost all cases, however, the data is presented in incomplete and inadequately detailed formats. Many analyses omit key emission sources such as farm fuel use or input production. Clear, accessible, *complete* analyses and graphs have not yet been produced. This report seeks to fill that gap.

Many current analyses omit key agricultural emissions data because they are based on categorization schemes stipulated by the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC)—categorizations that lead to a reporting of only a subset of agricultural emissions, including those from:

1. livestock enteric fermentation, i.e., digestion of grass and forage (methane, CH_4);
2. manure management (methane, CH_4, and nitrous oxide, N_2O);
3. agricultural soils, including emissions triggered by the addition of synthetic nitrogen fertilizer and manure (nitrous oxide, N_2O);
4. burning of crop residues (methane, CH_4, and nitrous oxide, N_2O); and
5. field-applied lime, urea fertilizer, and other carbon-containing fertilizers (carbon dioxide, CO_2).

Table 1 and Figure 1 are examples of analyses based on IPCC Agriculture categories.[4]

Table 1. An example of Canadian agricultural emissions based on IPCC Agriculture categories.

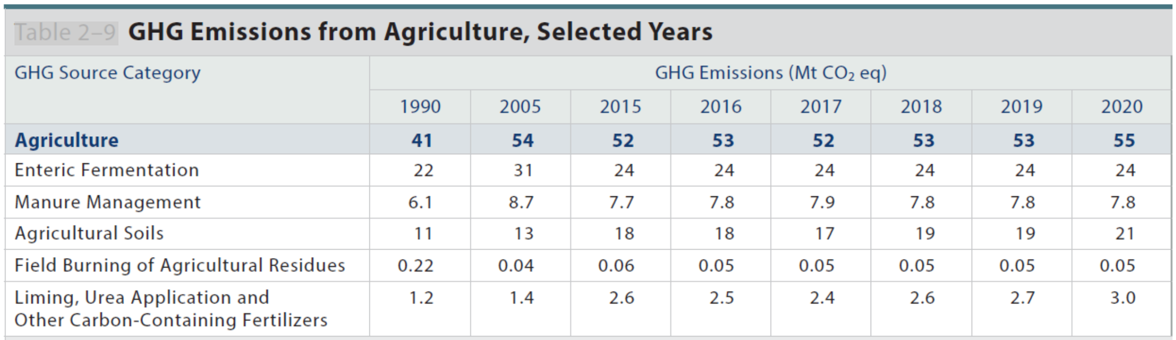

Table 2–9 **GHG Emissions from Agriculture, Selected Years**

GHG Source Category	GHG Emissions (Mt CO_2 eq)							
	1990	2005	2015	2016	2017	2018	2019	2020
Agriculture	**41**	**54**	**52**	**53**	**52**	**53**	**53**	**55**
Enteric Fermentation	22	31	24	24	24	24	24	24
Manure Management	6.1	8.7	7.7	7.8	7.9	7.8	7.8	7.8
Agricultural Soils	11	13	18	18	17	19	19	21
Field Burning of Agricultural Residues	0.22	0.04	0.06	0.05	0.05	0.05	0.05	0.05
Liming, Urea Application and Other Carbon-Containing Fertilizers	1.2	1.4	2.6	2.5	2.4	2.6	2.7	3.0

Source: Reproduced from ECCC, *National Inventory Report*.[5]

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[4] Environment and Climate Change Canada (ECCC) also produces tables based on "Economic Sectors" rather than "IPCC Sectors," and while the former are more complete, they still omit from "Agriculture" several emission sources, such as fertilizer manufacturing, electricity production, and machinery manufacturing.

[5] "NIR 2022 Part 1," 55.

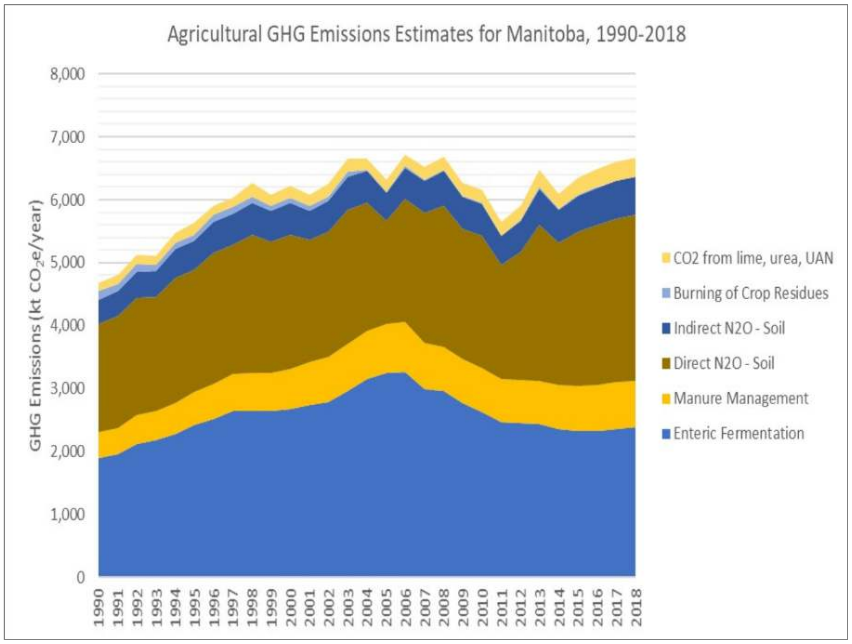

Figure 1. An example of a graph of agricultural emissions based on IPCC Agriculture categories.
Source: Reproduced from Manitoba Agriculture and Resource Development.[6]

IPCC-based reporting categorizes emissions from the production of machinery and fertilizer under “industrial processes and product use,” not agriculture. Emissions from farm fuel and electricity use are reported in “energy” and “transport.” Also, in many depictions of agricultural emissions, sources are coarsely aggregated, e.g., with graphs and tables often not distinguishing between nitrous oxide (N_2O) emissions from the application of synthetic nitrogen fertilizer versus N_2O emissions from the application of manure, and simply reporting all such emissions as coming from “agricultural soils” (see Table 1 or Figure 1).[7] To form the basis for planning on-farm emission-reduction measures or government policies or programs, more detailed and complete assessments are needed.

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[6] Manitoba Agriculture and Resource Development, “Environment > Climate Change > Agriculture and Climate Change.” Accessed June 11, 2021. https://www.gov.mb.ca/agriculture/.

[7] Foundational emissions data is not incomplete or coarsely aggregated; complete, detailed information is published by ECCC in the National Inventory Report (NIR) and elsewhere (see the “Key reports” section of this report for links). Rather, nearly all analyses (tables, graphs, reports) omit key emissions sources and fail to adequately disaggregate.

Part 1. A step toward a more complete picture of agricultural GHG emissions

As part of its work toward the 2019 publication of its report *Tackling the Farm Crisis and the Climate Crisis*, the NFU assembled a more complete picture of agricultural emissions—one that included production of fertilizer and farm machinery as well as on-farm fuel and energy use. Figure 2, below, is an example.

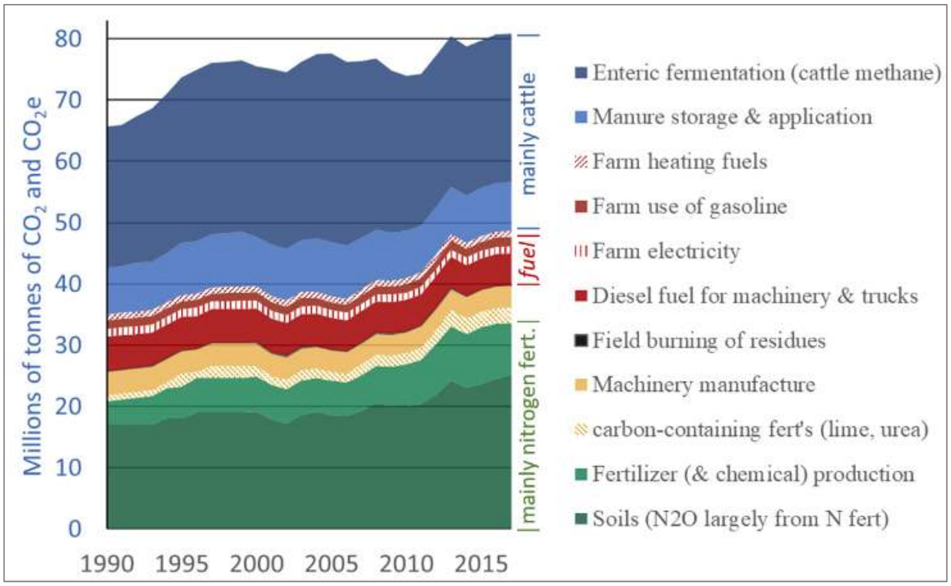

Figure 2. First attempt to create a more complete view of Canadian agricultural emissions, 1990–2017.
Source: Reproduced from: NFU, *Tackling the Farm Crisis and the Climate Crisis*.[8]

This first attempt at a more complete picture combined data from two sources:

1. ECCC, based on IPCC categorization;[9] and
2. James Dyer, Ray Desjardins, and coauthors[10] for emissions from on-farm diesel, gasoline, natural gas, and electricity use and production of fertilizer and machinery.[11]

When emissions from farm energy use and manufacture of farm inputs were added to IPCC Agriculture categories, total emissions were nearly a third higher than the sum of the IPCC Agriculture categories alone. Although Figure 2 represents a step forward, a more comprehensive analysis was needed.

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[8] Darrin Qualman and National Farmers Union, "Tackling the Farm Crisis and the Climate Crisis: A Transformative Strategy for Canadian Farms and Food Systems" (Saskatoon: NFU, 2019), https://www.nfu.ca/wp-content/uploads/2020/01/Tackling-the-Farm-Crisis-and-the-Climate-Crisis-NFU-2019.pdf.

[9] Environment and Climate Change Canada, "Canada's Official Greenhouse Gas Inventory: A. Tables IPCC Sector Canada," accessed June 11, 2021, https://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/A-Tables-IPCC-Sector-Canada/?lang=en; Environment and Climate Change Canada, "National Inventory Report 1990–2019: Greenhouse Gas Sources and Sinks in Canada," Part 1 (Ottawa: ECCC, 2021).

[10] J. Dyer et al., "Integration of Farm Fossil Fuel Use with Local Scale Assessments of Biofuel Feedstock Production in Canada," in *Efficiency and Sustainability in Biofuel Production*, Ed. B. Gikonyo (New York: Apple Academic Press, 2015); J. Dyer et al., "The Fossil Energy Use and CO_2 Emissions Budget for Canadian Agriculture," in *Sustainable Energy Solutions in Agriculture* (Boca Raton: CRC Press, 2014); and J. Dyer and R. Desjardins, "Carbon Dioxide Emissions Associated with the Manufacturing of Tractors and Farm Machinery in Canada," *Biosystems Engineering* 93, no. 1 (2006). Data for 2014 from J. Dyer, on request.

[11] Data from Dyer et al. specify emissions for 1991, 1996, 2001, 2006, 2011, and 2014, so must be interpolated and extrapolated. Emissions from energy use and machinery manufacture fluctuated little, so interpolation and extrapolation were straightforward. But emissions from fertilizer production rose sharply, so the NFU used a coefficient from Dyer et al. (4.05 tonnes CO_2e / tonne of actual N) and Stats Can data on applied N tonnage (Tables 32-10-0039-01 and 32-10-0274-01). We applied an efficiency adjustment: assuming nitrogen plants became 0.33 percent more efficient each year. This is based on Vaclav Smil, *Energy in Nature and Society* (Cambridge: MIT Press, 2008), Fig. 10.6. A larger efficiency adjustment may have been more appropriate.

Part 2. A comprehensive, detailed picture of agricultural GHG emissions

Between 2019 and 2022, we identified additions and refinements that could improve our emissions numbers and graphs. The result is Figure 3—a comprehensive picture of Canadian agricultural emissions and soil-atmosphere fluxes, now updated to take account of *NIR 2022* methodology changes and data revisions.

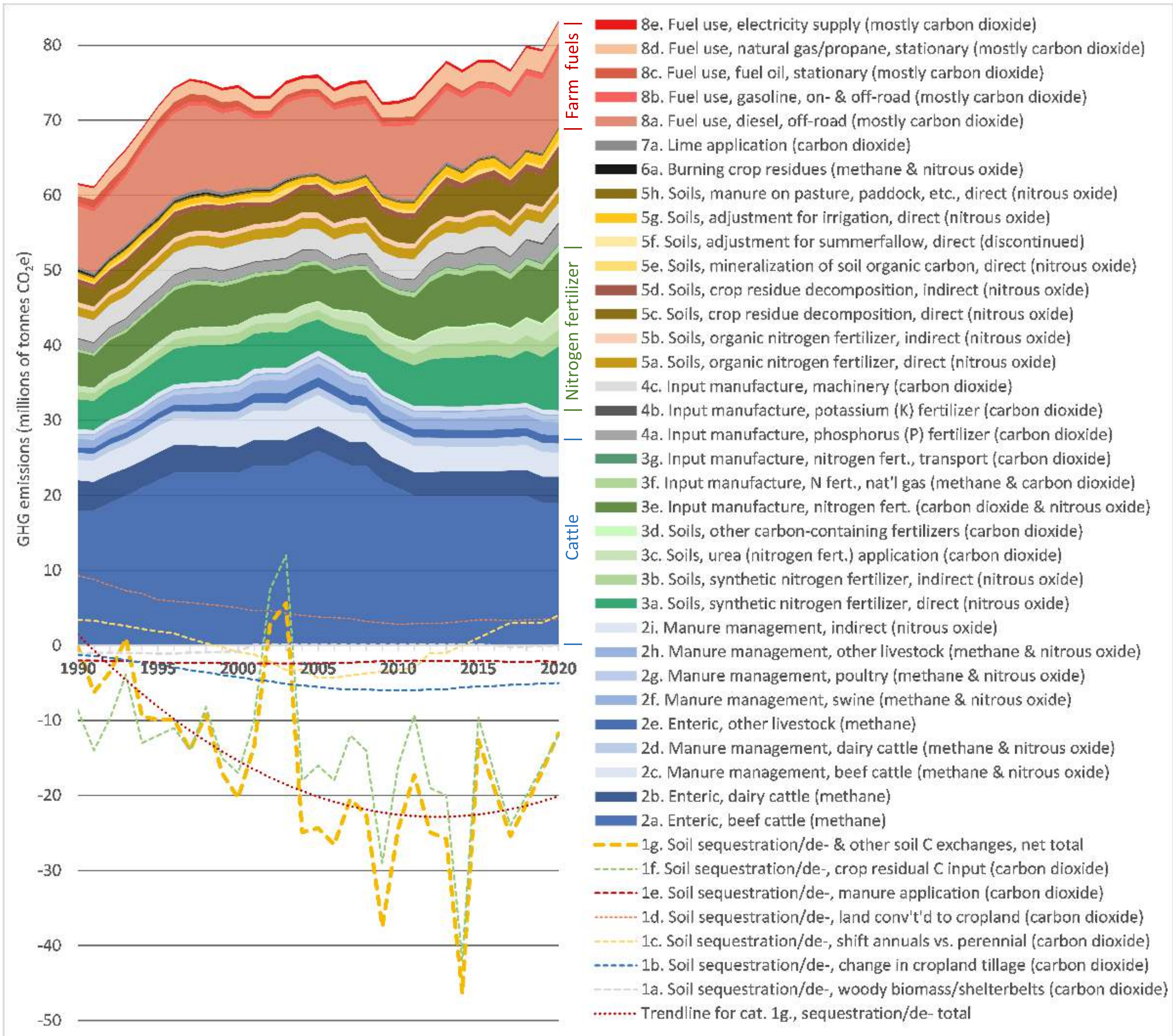

Figure 3. Comprehensive, detailed picture of Canadian agricultural emissions and fluxes, 1990–2020
Sources: ECCC, *National Inventory Report 1990–2020*, Part 1, Tables 5-1, 6-1, and 6-9 (with data for years omitted from the Tables provided by ECCC); Additional data and sub-categorizations of published data provided by ECCC upon request; ECCC, Common Reporting Format (CRF) Tables; Data from Dyer et al.; other sources; and NFU own calculations. The vast majority of categories are based on ECCC NIR data. For complete and detailed sources and notes for each category, see Part 4, below.

Note that in the graph (Figure 3) and other parts of this report we use the term "soil sequestration/de-" to refer to categories that can include sequestration (atmospheric CO_2 captured as soil carbon) and the reverse: *desequestration* (soil carbon released as atmospheric CO_2). A key concept is that this is a *reversible* process: soils can sequester carbon for a time and then changes in farming practices or climatic conditions can cause those soils to release/desequester carbon and later another change can cause them to again sequester, and so on and so on. Below, we include further explanations regarding this reversibility of sequestration and desequestration and why "desequestration" differs from "emissions."

Part 3. A high-level analysis of Canadian agricultural emissions and trends

In this Part, we provide general observations on some of the major components of the emissions depicted in Figure 3. In Part 4, we provide detailed notes and data sources for each emissions category in the graph.

A. Canadian agricultural GHG emissions are rising

The graph's top line rises from 61.5 million tonnes (Mt) carbon dioxide equivelant (CO_2e) in 1990 to 83.2 Mt in 2020[12]—a rise of 35 percent. Over a more recent period, agricultural emissions are up from 76.1 Mt in 2005—Canada's reference year for its international commitments. These emission values do not include adjustments for soil carbon sequestration or other carbon/CO_2 exchanges between soils and the atmosphere.

B. Rising emissions from nitrogen fertilizer use are driving up total emissions

The top line of the graph is rising because nitrogen-fertilizer-related emissions are rising. In the graph, emissions from the production and use of nitrogen fertilizer are recorded in seven categories:

3a. Direct emissions from farm fields (nitrous oxide, N_2O);
3b. Indirect emissions—off-site emissions from nitrogen fertilizer runoff, leaching, or volatilization (N_2O);
3c. Emissions from the carbon in granular urea fertilizer (carbon dioxide, CO_2);
3d. Emissions from the carbon in some other nitrogen fertilizers (CO_2);
3e. Emissions from nitrogen fertilizer production facilities (mostly CO_2, but also N_2O);
3f. Upstream emissions from the production and processing of the natural gas used in the production of nitrogen fertilizer (methane, CH_4, and CO_2); and
3g. Emissions from transport of fertilizer to distribution and retail facilities and onward to farms (mostly CO_2).

Emissions from nitrogen fertilizer production and use have more than doubled since 1990, driven by rising application rates and tonnage. ECCC explains: "inorganic nitrogen consumption has more than doubled, from 1.2 Mt N in 1990 to 2.9 Mt N in 2020."[13] See Figure 4. Based on current trends, a business-as-usual scenario could see fertilizer-related emissions nearly double again by 2050. To counter this strong upward trend and inflect the line downward, vigorous policy interventions are needed. In 2020, total emissions related to nitrogen fertilizer (from all seven categories) were 22.2 Mt CO_2e—making this the second largest source, after cattle (see next).

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[12] Unless otherwise specified, emissions units are millions of tonnes of carbon dioxide equivalent per year, i.e., Mt CO_2e per year.

[13] "*NIR 2022* Part 1," 145.

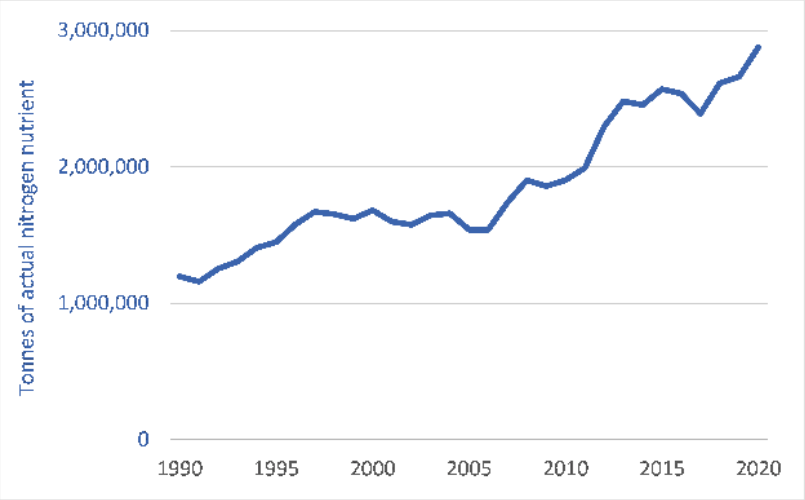

Figure 4. Canadian nitrogen fertilzer consumption, actual N nutrient, 1990–2020.
Sources: Statistics Canada Tables 32-10-0039-01 and 32-10-0274-01.

C. Cattle are the largest source of Canadian agricultural GHG emissions

Emissions directly attributed to cattle totalled 26.9 Mt CO_2e in 2020 and are reported in four categories:

- 2a. Enteric, beef cattle (CH_4);
- 2b. Enteric, dairy cattle (CH_4);
- 2c. Manure management, beef cattle (N_2O and CH_4); and
- 2d. Manure management, dairy cattle (N_2O and CH_4).

Enteric emissions come out of the mouths of cattle and other “ruminants” as a result of stomach bacteria metabolism creating methane (CH_4) during the digestion of grass and forage. Enteric methane is the largest component of cattle emissions: 19.0 Mt CO_2e from beef cattle in 2020 and 3.5 Mt from dairy cattle.

D. Emissions directly attributed to cattle are declining

Emissions attributed to cattle have been declining since 2005, as the size of the Canadian herd has declined. Figure 5 shows cattle numbers. Note how the shape of the top line echoes the shape of the emissions curves at the bottom of Figure 3. Efficiency gains have also helped decrease emissions.

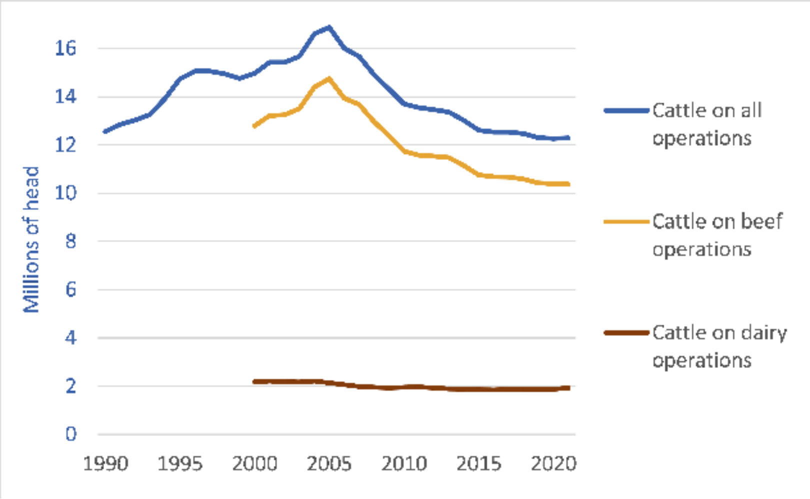

Figure 5. Cattle on farms in Canada, 1990–2021.
Source: Statistics Canada Table 32-10-0130-01.

Had cattle numbers remained near 2005 levels, or had numbers continued to rise as they did in the 1990-to-2005 period, overall agricultural emissions today (the top line in Figure 3) would be above 90 or 100 Mt CO_2e per year, rather than at 83 Mt. Declining emissions from cattle serve to countervail rising emissions from nitrogen fertilizer production and use—moderating the overall rate of increase in agricultural emissions.

E. There is no clear boundary for quantifying cattle-related emissions

Enteric and manure-management-related emissions for cattle totalled 26.9 Mt CO_2e in 2020. It is easy to think of those as comprising "emissions from cattle" and to think of nitrogen-related emissions or similar categories as "emissions from the crop sector." But, of course, a large portion of the Canadian crop is feedgrain and a significant portion of total farm fuel is used in beef and dairy production. Hence, a significant portion of nearly every category in Figure 3 could be counted toward emissions from cattle, such that beef- and dairy-related emissions may contribute more than 40 percent of all agricultural emissions in Canada.

This is not to assail beef or dairy production. To the contrary, cattle can be vital parts of biodiverse, nutrient-cycling ecosystems—core to regenerative agriculture, agroecology, mixed farming, and a range of solutions we must consider. Cattle can enable us to produce food on land that should not be cropped, and cattle or other ruminants are crucial to healthy grassland ecosystems. As the NFU details in *Tackling the Farm Crisis and the Climate Crisis*, having grazing animals on the landscape is *natural* and *beneficial*. Please read that report for a balanced view of the place of cattle in the sustainable agroecosystems of the future. That said, however, we must also acknowledge that emissions from beef and dairy production go far beyond manure and enteric emissions; encompass millions of tonnes reported under fertilizer and energy use; and are very high. These high emissions mean that we must make changes to cattle production systems if we are to reduce overall agricultural emissions in line with Canada's commitments and planetary limits.

F. There are large uncertainties and interpretive complexities regarding cattle and methane

This report presents best estimates of Canadian agricultural emissions and wherever possible stays close to published ECCC data and UN reporting norms. Although delving into all the details surrounding each emission source and process is beyond the scope of this report, it is, however, important to note, if only in passing, some factors that make interpretation of emissions data for livestock production more complex:

1. For millions of years, Earth has hosted huge numbers of ruminant animals that have emitted enteric methane,[14] so large flows of ruminant methane are a natural part of Earth's biosphere;
2. The biosphere and atmosphere also include huge methane *sinks* (locations/processes wherein methane is broken down),[15] many of which are increased or decreased by grazing, other agricultural practices, desertification, and other human actions and impacts; and
3. Quantification of methane sources and sinks entails large uncertainties.[16]

There is a disconnect between the *quantification* of emissions tonnages from cattle and the *interpretation* of those reported emissions. Consider this hypothetical: If the fossil fuel sector was a source only of carbon dioxide but not of methane, then current atmospheric methane concentrations would be much closer to long-term historical levels and therefore methane and cattle might not be seen as contributing to climate change. That said, from many sources, humans have *tripled* atmospheric concentrations of methane.[17] Therefore, all sectors must work rapidly to bring down methane emissions and concentrations.

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[14] Felisa A. Smith et al., "Exploring the Influence of Ancient and Historic Megaherbivore Extirpations on the Global Methane Budget," *Proceedings of the National Academy of Sciences* 113, no. 4 (January 26, 2016).

[15] Marielle Saunois et al., "The Global Methane Budget 2000-2017," *Earth System Science Data* 12 (2020).

[16] Saunois et al.

[17] United States Environmental Protection Agency, "Climate Change Indicators: Atmospheric Concentrations of Greenhouse Gases," Reports and Assessments, July 21, 2021, https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases.

G. Emissions from other livestock are larger than they might appear

In Figure 3, emissions from other livestock (poultry, hogs, etc.) appear to be small—totalling just 3.9 Mt CO_2e per year, mostly from manure management. However, these values omit emissions from feedgrain production—emissions reported in categories such as 3a, N_2O emissions from soils as a result of synthetic nitrogen application. Feedgrain-related emissions probably make up the bulk of emissions related to pork and poultry meat production, thereby obscuring the emissions footprint from these production systems.

H. Fuel and energy use is a larger component than previously understood

When the NFU compiled its first assessment of agricultural emissions (Figure 2), we calculated that farm fuel and energy use accounted for about 11 percent of total agricultural emissions. Having had three further years to explore and interpret data from multiple sources, we now calculate that on-farm energy use is a larger component, accounting for 17 percent of total agricultural emissions (Table 3). In Figure 3, emissions from farm fuel and energy use are divided into five categories (all predominantly CO_2):

- 8a. diesel fuel, off-road only (farmers' on-road diesel use would add very little, especially as we have set the boundary for this analysis at the farm gate, i.e., excluding post-farm transport);
- 8b. gasoline, on- and off-road;
- 8c. fuel oil, light and heavy, for stationary uses;
- 8d. natural gas and propane for stationary applications such as building heating and grain drying; and
- 8e. emissions from the fossil-fuel-fired electricity-generating stations that supply many farms.

I. Manufacturing of fertilizers and other farm inputs is significant and thus so too are fossil fuels and CO_2

This report and its graphs and tables include emissions from the production of four types of farm inputs:

- phosphorus fertilizer (category 4a);
- potassium fertilizer (4b);
- nitrogen fertilizer (3e, 3f, and 3g); and
- farm machinery (4c).

It is likely that these four—especially nitrogen and machinery—account for the bulk of emissions from the production of all farm inputs. Nonetheless, future editions of this report may be able to add categories for pesticides, plastics, etc. For example, emissions from the production of agricultural plastics appear to be about 0.12 Mt CO_2e per year from the 62,000 tonnes of agricultural plastics consumed annually.[18]

Farm input production is a significant part of overall agricultural emissions. Adding up all emissions from the production of agricultural machinery and fertilizers yields a total of 14.0 Mt CO_2e per year or 16.8 percent of total agricultural emissions.[19] Moreover, much of this is CO_2 from fossil fuels. When we add these emissions to those from farm fuel and energy use (another 17 percent of total emissions, see Table 3), we begin to see that about a third of total agricultural emissions are related to fossil fuels and CO_2.[20] This is a different picture than that often presented wherein almost all agricultural GHGs are methane and nitrous oxide (see, for example, Figure 1). Though these latter gases are central to the project of reducing agricultural emissions, it is a mistake to think that reducing fossil-fuel-related CO_2 emissions is not equally important. Fossil fuels are, by far, the largest input into Canadian food production systems.

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[18] Cleanfarms, "Agricultural Plastic Characterization and Management on Canadian Farms," submitted to: Environment and Climate Change Canada (Etobicoke, ON: Cleanfarms, 2021), https://cleanfarms.ca/wp-content/uploads/2021/08/Project-Building-a-Canada-Wide-Zero-Plastic-Waste-Strategy-for-Agriculture.pdf.

[19] This is based on the sum of categories 3e, 3f, 3g, 4a, 4b, and 4c. Categories 3c and 3d are excluded.

[20] The total would be more than one-third if CO_2 from in-field lysis of urea and UAN nitrogen fertilizer were included, and there are arguments for doing so because the C in that CO_2 is derived from fossil fuels and added in fertilizer production facilities.

Further, it may be that the *largest* portion of agricultural emissions reductions will eventually come from reductions in fossil-fuel use. Consider: Reducing enteric methane emissions from livestock by even 20 percent will be challenging. Similarly, reducing emissions from fertilizer use by 30 percent is possible, but it is hard to see how we can achieve, say, double that reduction. In contrast, it should be possible, as we move through the 2020s, 2030s, and beyond, to slash CO_2 emissions from fossil fuel and energy use—from manufacturing, mining, and other industrial processes; from the heating of farm homes and buildings; and, later and with more challenges, from farm machinery. Though perhaps a lower priority for agricultural emission reduction now, fossil fuel use may eventually yield the *largest* reductions.

J. Land use changes, carbon exchanges, and soil sequestration

The preceding focuses on agricultural greenhouse gas *emissions*. In addition to these emissions, there are also *exchanges* of carbon/CO_2 between the atmosphere and agricultural soils—some going one direction and some going the opposite. The most oft-mentioned example is soil carbon sequestration as a result of reductions in tillage: “no-till,” “zero-till,” “direct seeding,” or even “strip tillage.”

Opinions differ regarding how to *account* for these exchanges.[21] Some people advocate subtracting the tonnage of these soil-atmosphere carbon/CO_2 exchanges from the emissions outlined above—suggesting, for example, that we should net out roughly 20 million tonnes of soil carbon sequestration against the 83 million tonnes of GHG emissions to create a measure of “net emissions.” The NFU, however, believes that there are good reasons *not* to do so. Drawing on extensive published science and expert opinion, the NFU has detailed why GHG emissions and soil-atmosphere exchanges (including soil carbon sequestration resulting from reduced tillage) should be kept separate when doing GHG accounting. Please see the NFU’s 2021 submission to ECCC on this issue.[22] While soil carbon gains are *extremely* positive and contribute immensely to ecosystem integrity, soil health, water retention, drought resilience, and climate adaptation, soil carbon gains should not be seen as offsetting, zeroing out, or otherwise erasing actual emissions, especially those from fossil fuels.

Nonetheless, carbon/CO_2 exchanges between soils and the atmosphere as a result of changes in agricultural practices and increases in biomass inputs are large—totalling millions of tonnes per year. Taking our cues from ECCC, Figure 3 and Table 3 quantify these exchanges in six categories (all CO_2):

1a. Changes in woody biomass incl. additions or removals of tree rows, shelterbelts, etc.;
1b. Changes/reductions in tillage of croplands;
1c. Shifts in the balance between perennial and annual crop area;
1d. Land converted to cropland (mostly forest land cleared for farming);
1e. Manure application; and
1f. Crop residual carbon input.

Detailed explanations of these categories are provided in Part 4.

Note that categories 1e and 1f are new in this Second Edition, as a result of changes in methodologies between *NIR 2021* and *NIR 2022*. This has caused very large increases in the total amount of soil carbon sequestration reported. For example, for the year 2019, *NIR 2021* lists values that total 5.9 Mt CO_2e of sequestration per year. In contrast, *NIR 2022* lists values that total 16.7 Mt—nearly three times as high. Changes in other years as a result of altered methodologies are even more striking. At the extreme, for 2014, *NIR 2021* lists values that total 9.9 Mt CO2e of sequestration per year. *NIR 2022* lists values that

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[21] A distinction can be made between emissions reporting (quantifying tonnage) and emissions accounting (which adds in an element of interpretation or an assignment to larger categories).

[22] National Farmers Union, “Submission to the Public Comment Period for the Federal Government’s Draft Greenhouse Gas Offset Credit System Regulations” (Saskatoon: NFU, 2021), https://www.nfu.ca/wp-content/uploads/2021/05/Fedl-Regulations-for-Offset-Protocols-NFU-submission-May-2021-Final.pdf.

total 46.4—nearly *five* times as high. The major change is the new inclusion of "crop residual carbon input"—the idea that larger crops and increased crop biomass result in larger transfers of carbon/CO_2 to soils. See Appendix A for more details.

While it is prudent for all of us working on agricultural-emission-reduction policy development to adopt the new methodologies, such large changes, especially coming this late in the game (we are midway through the fourth decade of the climate emergency) can have the effect of undermining faith in modelled and reported values for emissions and soil-atmosphere exchanges. On the one hand, dramatically altered methodologies are improvements, but they are simultaneously evidence of significant problems, lags, and resource shortfalls within our measurement systems and ECCC.

Below are two tables from Canada's most recent National Inventory Report.[23] Negative values denote carbon/CO_2 flowing from the atmosphere into agricultural soils (sequestration) and positive values denote carbon/CO_2 flowing from agricultural soils to the atmosphere (desequestration). Note the very large negative values for "Crop residual C input."

Table 2. Two tables showing exchanges of carbon/CO_2 between soils and the atmosphere.

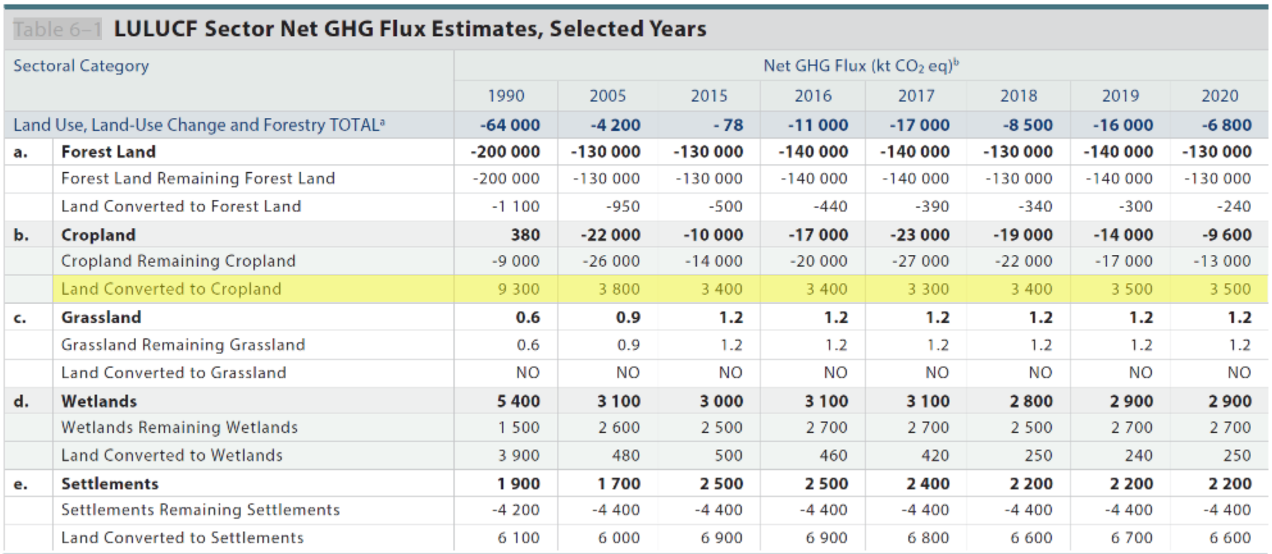

Table 6–1 **LULUCF Sector Net GHG Flux Estimates, Selected Years**

Sectoral Category		Net GHG Flux (kt CO_2 eq)[b]							
		1990	2005	2015	2016	2017	2018	2019	2020
Land Use, Land-Use Change and Forestry TOTAL[a]		**-64 000**	**-4 200**	**- 78**	**-11 000**	**-17 000**	**-8 500**	**-16 000**	**-6 800**
a.	**Forest Land**	**-200 000**	**-130 000**	**-130 000**	**-140 000**	**-140 000**	**-130 000**	**-140 000**	**-130 000**
	Forest Land Remaining Forest Land	-200 000	-130 000	-130 000	-140 000	-140 000	-130 000	-140 000	-130 000
	Land Converted to Forest Land	-1 100	-950	-500	-440	-390	-340	-300	-240
b.	**Cropland**	**380**	**-22 000**	**-10 000**	**-17 000**	**-23 000**	**-19 000**	**-14 000**	**-9 600**
	Cropland Remaining Cropland	-9 000	-26 000	-14 000	-20 000	-27 000	-22 000	-17 000	-13 000
	Land Converted to Cropland	9 300	3 800	3 400	3 400	3 300	3 400	3 500	3 500
c.	**Grassland**	**0.6**	**0.9**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
	Grassland Remaining Grassland	0.6	0.9	1.2	1.2	1.2	1.2	1.2	1.2
	Land Converted to Grassland	NO	NO	NO	NO	NO	NO	NO	NO
d.	**Wetlands**	**5 400**	**3 100**	**3 000**	**3 100**	**3 100**	**2 800**	**2 900**	**2 900**
	Wetlands Remaining Wetlands	1 500	2 600	2 500	2 700	2 700	2 500	2 700	2 700
	Land Converted to Wetlands	3 900	480	500	460	420	250	240	250
e.	**Settlements**	**1 900**	**1 700**	**2 500**	**2 500**	**2 400**	**2 200**	**2 200**	**2 200**
	Settlements Remaining Settlements	-4 200	-4 400	-4 400	-4 400	-4 400	-4 400	-4 400	-4 400
	Land Converted to Settlements	6 100	6 000	6 900	6 900	6 800	6 600	6 700	6 600

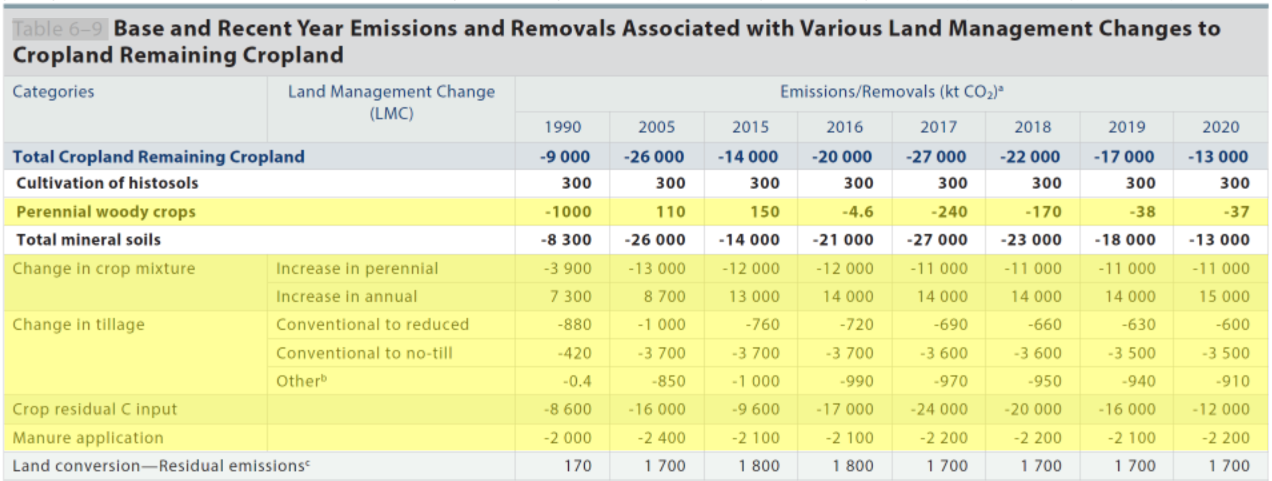

Table 6–9 **Base and Recent Year Emissions and Removals Associated with Various Land Management Changes to Cropland Remaining Cropland**

Categories	Land Management Change (LMC)	Emissions/Removals (kt CO_2)[a]							
		1990	2005	2015	2016	2017	2018	2019	2020
Total Cropland Remaining Cropland		**-9 000**	**-26 000**	**-14 000**	**-20 000**	**-27 000**	**-22 000**	**-17 000**	**-13 000**
Cultivation of histosols		**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**
Perennial woody crops		**-1000**	**110**	**150**	**-4.6**	**-240**	**-170**	**-38**	**-37**
Total mineral soils		**-8 300**	**-26 000**	**-14 000**	**-21 000**	**-27 000**	**-23 000**	**-18 000**	**-13 000**
Change in crop mixture	Increase in perennial	-3 900	-13 000	-12 000	-12 000	-11 000	-11 000	-11 000	-11 000
	Increase in annual	7 300	8 700	13 000	14 000	14 000	14 000	14 000	15 000
Change in tillage	Conventional to reduced	-880	-1 000	-760	-720	-690	-660	-630	-600
	Conventional to no-till	-420	-3 700	-3 700	-3 700	-3 600	-3 600	-3 500	-3 500
	Other[b]	-0.4	-850	-1 000	-990	-970	-950	-940	-910
Crop residual C input		-8 600	-16 000	-9 600	-17 000	-24 000	-20 000	-16 000	-12 000
Manure application		-2 000	-2 400	-2 100	-2 100	-2 200	-2 200	-2 100	-2 200
Land conversion—Residual emissions[c]		170	1 700	1 800	1 800	1 700	1 700	1 700	1 700

Source: Reproduced from ECCC, National Inventory Report.[24]
Notes: Yellow-highlighted rows indicate categories used in this report.

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[23] "*NIR 2022* Part 1," 170 & 188.

[24] "*NIR 2022* Part 1," Tables 6-1 & 6-9.

Please note several points about the values in these tables:

A. Reductions in tillage, while the most-often discussed category, is not where we see the largest carbon/CO_2 flows. In recent years, tillage-related sequestration has been approx. 5 Mt per year.

B. Crop residual carbon input (which subsumes the previous category “Reduction in summerfallow area”) is a much larger factor in moving carbon/CO_2 from the atmosphere to soils. This resulted in sequestration averaging roughly 20 Mt CO_2e per year in recent years.

C. Changes in the mix of annual versus perennial crops is another factor. Shifts that result in a smaller area of annual crops and a larger area of perennials are reported as net transfers of carbon/CO_2 from the atmosphere to soils. In the table above, the overall balance of those changes in crop mix have resulted in carbon/CO_2 exchanges ranging from −4.3 Mt (i.e., net sequestration) in 2005 to +4.0 Mt (desequestration[25]) in 2020. (Such examples of reversals of carbon-flow direction are one reason why soil sequestration should not be seen as an “offset” to essentially permanent emissions from fossil fuel combustion.)

D. “Land converted to cropland” (the creation of new farmland, mainly from forest) also creates carbon/CO_2 exchanges—desequestration ranging from 2.8 to 3.5 Mt CO_2e per year in recent years.

E. Overall, sequestration—the transfer of carbon/CO_2 from the atmosphere to soils—is declining, though highly variable from year to year. Averaging the most recent five years for which data is available (2016–2020, inclusive) the six categories averaged −18.6 Mt CO_2e per year, i.e., sequestration of that amount. But several years earlier (2010–2014, inclusive), those same six categories together averaged −27.8 Mt—50 percent higher. Commenting on this recent downtrend, ECCC said in *NIR 2021* that “after peaking in the years 2006 to 2011, current net removals [by] cropland are ... lower ..., mainly as a result of increased conversion of perennial to annual crops on the Prairies and the declining effect of the adoption of conservation tillage on cropland that mainly occurred in the 1980s and 90s.”[26] In *NIR 2022*, ECCC explains the increase in sequestration rates followed by the recent decrease in this way:

> Changes in agricultural land management practices in Western Canada, such as the extensive adoption of conservation tillage combined with reduced summerfallow and increasing crop yields which has, in turn, increased C input to soils, have resulted in an increase in net removals of CO_2 [via] Cropland in the 1990–2006 period. This trend was further augmented by reductions in the conversion of other lands to Cropland over the same period. However, since 2006, a decrease in the adoption rate of conservation tillage, the conversion of perennial lands to annual crop production and, in recent years, some increases in the conversion of Forest Land and Grassland to Cropland have resulted in a levelling off and decline in Cropland removals.[27]

F. ECCC does not yet report data on carbon/CO_2 desequestration from the destruction of wetlands on agricultural land.[28] If reported, this would be a large source of CO_2. Conversations with experts indicate that soil carbon/CO_2 flows from wetlands destruction on Prairie farmland could total 3 to 4 Mt CO_2e per year.[29] If further research reveals that to be an accurate estimate, values for overall soil carbon sequestration could be 20 to 25 percent lower than those in Figure 3 and Table 3.

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[25] As explained above and below, this report distinguishes between “emissions” (largely non-reversible and often the result of industrial processes or fossil fuel combustion) and “desequestration” (reversible soil-atmosphere carbon/CO_2 flows, often the result of changes in farming practices, land use, or climate).

[26] Environment and Climate Change Canada, “NIR 2021 Part 1,” “NIR Part 1,” 9. ECCC has indicated that the reporting of wetland loss emissions are part of its planned improvements.

[27] “*NIR 2022* Part 1,” 170–71.

[28] “*NIR 2022* Part 1,” Table 6-4.

[29] This estimate includes only carbon losses from soils and does not include increased emissions from subsequent fertilizer and input use or *decreased* emissions from the reduction of farm implement overlap, etc. Most likely, soil carbon losses represent the bulk of overall GHG flows that result from destruction of wetlands.

In concluding this section, let us acknowledge that many people believe that soil carbon sequestration *should* be legitimately subtracted from GHG emissions to yield some measure of "net emissions." They reject the argument sketched above and detailed elsewhere[30] that soil carbon sequestration should not be counted as negating, zeroing out, or offsetting emissions from fossil fuels and other sources. For a moment, let us accept that position. When we do, we see that it makes only a minor difference to our analysis of agricultural emissions. Sequestration averaging 18.6 Mt CO_2e per year (2016–2020, inclusive) would negate only 22 percent of agricultural emissions—leaving about 80 percent.

Moreover, the current trendline seems to indicate that sequestration will continue to decline as we move toward 2030 and beyond. Agriculture and Agri-Food Canada (AAFC) says that "it is projected that the annual rate of cropland soil carbon sequestration will decline...."[31] And if desequestration from destruction of wetlands on agricultural land were included, sequestration effects could be much lower. At the same time, while sequestration effects may continue to decline, emissions continue to rise at a rate of roughly 1 Mt per year.

Thus, while accelerating and maximizing carbon gains in agricultural soils is crucial—a *top* priority and a *huge* benefit—it must be understood that even very aggressive efforts and unprecedented successes in this area can provide only modest contributions to addressing agricultural emission challenges.[32]

Note to readers: The following section is technical—primarily intended for those who are seeking a deep understanding of emissions categories or sources and methodologies. Though of particular interest to readers who want to delve deeply into these issues, others may prefer to skim over the next section or to read it selectively.

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[30] National Farmers Union, "Submission to the Public Comment Period for the Federal Government's Draft Greenhouse Gas Offset Credit System Regulations."

[31] Agriculture and Agri-Food Canada, "An Overview of the Canadian Agriculture and Agri-Food System" (Ottawa: AAFC, April 2016), 14, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.510.7186&rep=rep1&type=pdf.

[32] The exception to this statement might be a very significant shift from annual to perennial crops. Such a shift, however, implies similarly significant increases in cattle numbers, and enteric emissions from those animals would partly offset or perhaps even overwhelm increased sequestration tonnage. As we detail in our *Tackling* report, farms are systems, and changes in one area ripple out to create widespread changes in many areas. Emissions reduction requires systems thinking.

Part 4. Detailed notes, analysis, and sources for emissions categories

Table 3 summarizes values for Figure 3 categories and, for each, its percentage of total agricultural emissions.

Table 3. Emissions values (Mt CO_2e per year) and percent of total for each category.

	1990	1995	2000	2005	2010	2015	**2020**	% of 2020 ag total
8e. Fuel use, electricity supply (mostly carbon dioxide)	0.3	0.3	0.4	0.4	0.4	0.4	**0.3**	0.3%
8d. Fuel use, natural gas/propane, stationary (mostly carbon dioxide)	1.5	1.6	1.7	1.5	1.8	2.5	**2.7**	3.3%
8c. Fuel use, fuel oil, light and heavy, stationary (mostly carbon dioxide)	0.8	1.0	0.8	0.5	0.6	0.3	**0.2**	0.2%
8b. Fuel use, gasoline, on- and off-road (mostly carbon dioxide)	0.5	0.5	0.5	0.5	0.6	0.6	**0.7**	0.8%
8a. Fuel use, diesel, off-road (mostly carbon dioxide)	8.1	11.1	10.5	10.1	9.8	9.3	**10.3**	12.4%
Subtotal for farm fuel/energy use	***11.2***	***14.5***	***13.9***	***13.0***	***13.2***	***13.1***	***14.2***	***17.0%***
7a. Lime application (carbon dioxide)	0.4	0.5	0.5	0.2	0.2	0.2	**0.2**	0.2%
6a. Burning crop residues (methane & nitrous oxide)	0.2	0.2	0.1	0.0	0.0	0.1	**0.1**	0.1%
Subtotal for 6a and 7a	***0.6***	***0.7***	***0.6***	***0.2***	***0.2***	***0.3***	***0.3***	***0.3%***
5h. Soils, manure on pasture, etc., direct (nitrous oxide)	0.2	0.3	0.2	0.3	0.2	0.2	**0.2**	0.2%
5g. Soils, adjustment for irrigation, direct (nitrous oxide)	0.6	0.7	0.7	0.8	0.9	1.1	**1.3**	1.6%
5f. Soils, adjustment for summerfallow, direct (discon'd in NIR 2022)	-	-	-	-	-	-	**-**	-
5e. Soils, mineralization of soil organic carbon, direct (nitrous oxide)	0.2	0.3	0.3	0.5	0.4	0.7	**0.8**	1.0%
5d. Soils, crop residue decomposition, indirect (nitrous oxide)	0.6	0.6	0.6	0.7	0.7	0.8	**0.9**	1.1%
5c. Soils, crop residue decomposition, direct (nitrous oxide)	2.5	2.6	2.9	3.1	3.3	4.0	**4.5**	5.4%
5b. Soils, organic nitrogen fertilizer, indirect (nitrous oxide)	0.6	0.7	0.7	0.7	0.7	0.7	**0.7**	0.8%
5a. Soils, organic nitrogen fertilizer, direct (nitrous oxide)	1.2	1.3	1.4	1.5	1.4	1.5	**1.5**	1.8%
Subtotal for soils (not attributed to synthetic N fertilizer or livestock)	***5.9***	***6.5***	***6.8***	***7.6***	***7.6***	***9.0***	***9.9***	***11.9%***
4c. Input manufacture, machinery (carbon dioxide)	2.9	2.9	2.9	2.7	2.7	2.6	**2.6**	3.1%
4b. Input manufacture, potassium (K) fertilizer (carbon dioxide)	0.2	0.1	0.1	0.1	0.1	0.2	**0.3**	0.4%
4a. Input manufacture, phosphorus (P) fertilizer (carbon dioxide)	1.3	1.3	1.4	1.3	1.3	2.0	**2.6**	3.1%
Subtotal for input manufacture (excluding synthetic N fertilizer)	***4.4***	***4.3***	***4.4***	***4.1***	***4.1***	***4.8***	***5.5***	***6.6%***
3g. Input manufacture, N fert, transport (carbon dioxide)	0.1	0.1	0.1	0.1	0.1	0.2	**0.2**	0.2%
3f. Input manufacture, N fert, natural gas (methane & carbon dioxide)	0.4	0.4	0.5	0.5	0.6	0.8	**0.9**	1.1%
3e. Input manufacture, N fertilizer (carbon dioxide & nitrous oxide)	4.5	5.1	5.6	4.8	5.6	7.1	**7.5**	9.0%
3d. Soils, other carbon-containing N fertilizer (carbon dioxide)	0.1	0.1	0.1	0.1	0.2	0.3	**0.3**	0.4%
3c. Soils, urea N fert application (carbon dioxide)	0.8	1.0	1.1	1.1	1.4	2.1	**2.5**	3.0%
3b. Soils, synthetic nitrogen fertilizer, indirect (nitrous oxide)	1.0	1.2	1.3	1.2	1.5	1.9	**2.3**	2.7%
3a. Soils, synthetic nitrogen fertilizer, direct (nitrous oxide)	4.0	4.4	4.8	4.2	5.2	6.6	**8.5**	10.2%
Subtotal for nitrogen fertilizer production and use	***10.9***	***12.3***	***13.5***	***12.0***	***14.6***	***19.0***	***22.2***	***26.6%***
2i. Manure management, indirect (nitrous oxide)	0.6	0.7	0.7	0.8	0.6	0.6	**0.6**	0.7%
2h. Manure management, other livestock (methane & nitrous oxide)	0.1	0.1	0.2	0.2	0.2	0.2	**0.2**	0.2%
2g. Manure management, poultry (methane & nitrous oxide)	0.6	0.6	0.7	0.7	0.8	0.8	**0.8**	1.0%
2f. Manure management, swine (methane & nitrous oxide)	1.1	1.3	1.6	1.9	1.6	1.7	**1.8**	2.1%
2e. Enteric, other livestock (methane)	0.7	0.8	1.1	1.3	1.1	1.1	**1.1**	1.3%
Subtotal for swine, poultry, and other livestock	***3.1***	***3.5***	***4.4***	***4.9***	***4.3***	***4.4***	***4.5***	***5.3%***
2d. Manure management, dairy cattle (methane & nitrous oxide)	1.0	1.0	1.0	1.0	1.1	1.1	**1.2**	1.5%
2c. Manure management, beef cattle (methane & nitrous oxide)	2.7	3.5	3.8	4.2	3.5	3.3	**3.2**	3.8%
2b. Enteric, dairy cattle (methane)	4.0	3.7	3.4	3.2	3.1	3.2	**3.5**	4.2%
2a. Enteric, beef cattle (methane)	18.0	22.0	23.0	26.0	21.0	20.0	**19.0**	22.8%
Subtotal for cattle enteric and manure management	***25.7***	***30.2***	***31.2***	***34.4***	***28.7***	***27.6***	***26.9***	***32.3%***
Total for all agricultural emissions	***61.5***	***71.8***	***74.6***	***76.1***	***72.6***	***78.1***	***83.2***	***100%***
1a. Soil sequestration/de-, change in woody biomass (carbon dioxide)	-1.0	-1.1	-0.8	0.1	0.1	0.2	**0.0**	
1b. Soil sequestration/de-, change in cropland tillage (carbon dioxide)	-1.3	-2.6	-4.2	-5.6	-6.0	-5.5	**-5.0**	
1c. Soil sequestration/de-, shift annuals vs. perennials (carbon dioxide)	3.4	1.9	-0.9	-4.3	-3.2	1.0	**4.0**	
1d. Soil sequestration/de-, land converted to cropland (carbon dioxide)	9.3	6.1	5.0	3.8	2.8	3.4	**3.5**	
1e. Soil sequestration/de-, manure application (carbon dioxide)	-2.0	-2.3	-2.4	-2.4	-2.1	-2.1	**-2.2**	
1f. Soil sequestration/de-, crop residual C input (carbon dioxide)	-8.6	-12.0	-17.0	-16.0	-16.0	-9.6	**-12.0**	
1g. Soil sequestration/de- and other soil C exchanges, net total	-0.2	-10.0	-20.3	-24.3	-24.5	-12.6	**-11.7**	

Sources: See below. Units: Mt CO_2e/year, and percentages

Beginning near the bottom of Table 3 and Figure 3 and working upward, the following are explanations of, commentaries on, and data sources for each of the 41 categories.

Soil-atmosphere exchange categories: sequestration and desequestration

All these categories involve carbon/CO_2. Negative numbers represent flows from the atmosphere *to soils*, i.e., sequestration. Positive numbers represent flows *from soils* to the atmosphere, i.e., desequestration. This latter term serves to distinguish these flows from "emissions." For just as sequestration (inflows to soils) can sometimes be reversed in subsequent years or decades, so too can desequestration (outflows from soil) be reversed. This reversibility makes soil carbon desequestration very different from *emissions*, especially those from fossil fuels.[33]

Sequestration/desequestration flows are indicated by the dotted lines near the bottom of the Figure 3 graph. The following text details each category and explains where the data was sourced. Note that these dotted lines on the graph do not affect the top line, i.e., total emissions, which were 83.2 Mt in 2020. This is because, as stated above, we do not believe that reversible exchanges such as soil carbon sequestration should be subtracted from emissions. Therefore, the graph does not include a line for "net emissions."

1a. Soil sequestration/de-, change in woody biomass, including additions or removals of shelterbelts

Carbon dioxide; −0.037 Mt CO_2e/y in 2020 (uncertainty range ±75%)

In *NIR 2022*, ECCC explains this category as including "emission and removal estimates of woody biomass include trees and shrubs that occur on agricultural lands as well as perennial woody crops such as vineyards, fruit orchards and Christmas trees."

Sources: ECCC, *NIR 2022*, Part 1, Ch. 6 and Table 6-9 (with data for years omitted from the Table provided by ECCC, on request). See also *NIR 2022,* Part 1, section 6.5.1.3.

1b. Soil sequestration/de-, change in cropland tillage

Carbon dioxide; −5.5 Mt CO_2e/y in 2020 (uncertainty range unknown)

Tillage tends to deplete soil carbon levels. Reductions in tillage can shift the balance between soil carbon losses and gains such that levels increase. That said, limits exist—there are equilibria or saturation levels. In the *NIR 2021*, ECCC notes that "After 2006, net removals remained relatively constant until 2011, but have since gradually declined to 4.2 Mt in 2019, largely as a result of the conversion of perennial lands to annual crop production, a decrease in the adoption rate of conservation tillage, and the fact that *soil C in lands previously converted to conservation tillage is approaching equilibrium*" [italics added].[34] ECCC reiterates that "the soil sink from past management changes is *approaching a steady state where organic C additions to the soil are balanced by losses of organic C from decomposition*" [italics added].[35] The trendline for this category has been upward since 2011, i.e., it is becoming *less* negative as reduced tillage

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[33] To comprehend the reversibility of soil-atmosphere carbon exchanges (at least as modelled by ECCC), consider a hypothetical piece of land. Initially, in the 1940s, it exists as forest at the northern edge of the Prairie grain belt. When that land is converted to cropland, it begins losing carbon. Three of four decades later, perhaps its soil carbon levels have begun to stabilize. Later still, the farmer stops summerfallowing and the land begins gaining carbon. A few years later, however, to control weed problems, the farmer resumes summerfallowing and the land resumes losing carbon. In the 1990s, the farmer again stops summerfallowing and adopts no-till cropping. The land resumes gaining carbon. In the 2000s, the land is switched to perennial forage and carbon gains continue, even accelerate. Then, around 2015, the land is transferred back into annual crop production and it begins losing carbon. The direction of carbon flows can be reversed again and again. Moreover, there are also shorter-term reversals: even when there are no changes in agronomic practices, unusually dry years can cause soils to lose carbon whereas wetter years with better growing conditions can cause carbon gains. Indeed, if our long-term climate turns hotter and dryer, overall soil carbon levels may be pushed down despite farmers' best efforts utilizing reduced tillage, etc.

[34] Environment and Climate Change Canada, "NIR 2021 Part 1," 143.

[35] Environment and Climate Change Canada, 159.

sequesters a declining tonnage each year. Moreover, AAFC projects that this decline in annual sequestrated tonnage will continue through 2030 and beyond.[36]

Sources: ECCC, *NIR 2022*, Part 1, Ch. 6 and Table 6-9 (with data for years omitted from the Table provided by ECCC, on request). See *NIR 2022* Part 1, section 6.5.1.1.

1c. Soil sequestration/de-, shift in annuals vs. perennials

Carbon dioxide; +4.0 Mt CO_2e/y in 2020 (uncertainty range unknown)

ECCC values in this category are modelled on the basis that shifts from annual to perennial crops increase soil carbon levels while shifts in the other direction cause carbon losses. In the early 2000s, a shift to perennials led to significant sequestration (−4.3 Mt CO_2e/y in 2005) whereas in recent years a shift back to annual crops has reversed the flow and resulted in desequestration of 4.0 Mt in 2020. ECCC explains that "since 2006 net removals have decreased..., mainly driven by the decrease in the proportion of perennial crops in the crop mixture."[37] The trendline is upward (increasing rates of desequestration), but unlike a measure such as reduced tillage, the trendline in this category could easily swing in the other direction if farmers changed their practices. See Table 2, above, for additional detail and numbers for this category.

Sources: ECCC, *NIR 2022*, Part 1, Ch. 6 and Table 6-9 (with data for years omitted from the Table provided by ECCC, on request). See *NIR 2022*, Part 1, section 6.5.1.1.

1d. Soil sequestration/de-, land converted to cropland

Carbon dioxide; +3.5 Mt CO_2e/y in 2020 (uncertainty range 2.5 Mt–4.5 Mt)

ECCC explains: "This subcategory includes the conversion of forest land and agricultural grassland to cropland. Emissions estimated and reported in Forest Land Converted to Cropland account for more than 90% of the total annual emissions in this category, which decreased from 9.2 Mt in 1990 to 3.5 Mt in 2020. Emissions associated to Grassland Converted to Cropland are relatively small."[38] As ECCC notes, the trendline is downward: desequestration is declining as the rate of conversion from forest to farmland slows.[39] However, rising farmland values and rising temperatures (allowing cropland areas to shift northward) may have an effect on this category and accelerate desequestration in coming decades.[40]

Sources: ECCC, *NIR 2022*, Part 1, Ch. 6 and Table 6-1 (with data for years omitted from the Table provided by ECCC, on request). See *NIR 2022*, Part 1, section 6.5.2.

1e. Soil sequestration/de-, manure application

Carbon dioxide; −2.2 Mt CO_2e/y in 2020 (uncertainty range unknown)

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[36] Agriculture and Agri-Food Canada, "An Overview of the Canadian Agriculture and Agri-Food System," 14.

[37] Environment and Climate Change Canada, "NIR 2021 Part 1," 159.

[38] "NIR 2022 Part 1," 193.

[39] In general, tonnage values in soil sequestration/de- categories can be positive or negative (unlike the "emissions" categories, below, which are always positive, i.e., sources of emissions). That said, this category—"land converted to cropland"—can only go as low as zero; because rather than recording negative values here, those would be recorded as "Land Converted to Forest Land" if it were the case that farmland was being converted to forest faster than the reverse.

[40] Matthew McClearn, "Study Says Climate Change Set to Open North to More Farming," *Globe and Mail*, February 17, 2020, https://www.theglobeandmail.com/canada/article-study-says-climate-change-set-to-open-north-to-more-farming/; Grace McGrenere, "Canada Could Gain 4.2 Million Square Kilometres of Agricultural Land as a Result of Climate Change," *Canadian Geographic*, March 10, 2020, https://www.canadiangeographic.ca/article/canada-could-gain-42-million-square-kilometres-agricultural-land-result-climate-change.

This category and the next (crop residual C input) are both new additions resulting from the major methodological changes ECCC instituted in *NIR 2022*. See Appendix A for more details on revised ECCC methodologies as they relate to this category.

ECCC explains this category this way: "A country-specific method using a manure-induced C retention factor (Liang et al., 2020) was developed to estimate soil C sink as a result of manure application to cropland soils. Estimates of SOC change occurred only in cases in which manure was applied to annual cropping systems. Manure applications to perennial land were considered to have no net impact on soil C due to a lack of empirical data to estimate a retention factor."[41]

Sources: ECCC, *NIR 2022*, Part 1, Ch. 6 and Table 6-9 (with data for years omitted from the Table provided by ECCC, on request). See *NIR 2022*, Part 1, section 6.5.1.

1f. Soil sequestration/de-, crop residual C input

Carbon dioxide; −12.0 Mt CO_2e/y in 2020 (uncertainty range unknown)

This category is a new addition resulting from the methodological changes in *NIR 2022*.

ECCC explains: "In this submission, the IPCC Tier 2 Steady State approach (IPCC, 2019) is also used for estimating soil C storage as impacted by the change in crop productivity/crop residue C input to soils based on yield estimates. As a result, the explicit inclusion of area-based summerfallow factors is eliminated as a separate driver of changes in cropland soil C. Removals of CO_2 associated with increases in C input to soils from reductions of summerfallow area are estimated based on changes in yield exclusively to avoid double counting as regional estimates of yield change inherently include the reduction in summerfallow."[42]

The idea underpinning this category is that higher crop yields and increased crop biomass result in larger transfers of carbon/CO_2 to soils. ECCC states that: "Since 1990, on average, major field crop yields increased by 23% for barley, 82% for canola, 41% for corn, 72% for spring rye and 36% for spring wheat. This increase in crop yield reflected in C inputs to soils from crop residues resulted in net removals of CO_2 by soils of 8.6 Mt in 1990, 16 Mt in 2005, and 12 Mt in 2020. Interannual variability is high throughout the time series, reflecting weather-related impacts to crop production...."[43]

The addition of this category to the NIR represents a large change to reporting of agricultural emissions and soil-atmosphere carbon/CO_2 fluxes—the addition of millions of additional tonnes of soil sequestration annually. At the extreme, for 2014, the change is more than 42 million tonnes—resulting in a near fivefold increase in annual sequestration. More recently, this category adds 12 Mt of sequestration in 2020.

See, also, Appendix A for more on these methodological changes.

Sources: ECCC, *NIR 2022*, Part 1, Ch. 6 and Table 6-9 (with data for years omitted from the Table provided by ECCC, on request). See *NIR 2022*, Part 1, section 6.5.1.

1g. Soil sequestration/de- and other soil-atmosphere carbon/CO_2 exchanges, net total

Carbon dioxide; −11.7 Mt CO_2e/y in 2020 (uncertainty range unknown)

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[41] "NIR 2022 Part 1," 189.

[42] "NIR 2022 Part 1," 187.

[43] "NIR 2022 Part 1," 188.

This is the sum of the six carbon/CO_2 exchange categories above: 1a. change in woody biomass; 1b. change in cropland tillage; 1c. shift in annuals vs. perennials; 1d. land converted to cropland; 1e, manure application; and 1f. crop residual C input. This net total shows the overall magnitude of all carbon/CO_2 exchanges between agricultural soils and the atmosphere. Evident in Figure 3, this measure appears to be declining, i.e., it is becoming less negative indicating a declining annual flow of carbon/CO_2 from the atmosphere into soils as a result of changes in tillage, rotations, land conversion, manure application, and crop residual C input. Sequestration, though significant, may be slowing.

Nonetheless, it is wholly possible that this category could increase dramatically (become more negative indicating an increase in sequestration rates) if the rate of conversion of forests to farmland falls and/or farmers begin shifting from annual to perennial crops. There is very significant potential—many millions of tonnes per year—from these two practices. On the other hand, however, the potentials from reductions in tillage are limited because of widespread adoption already. So it is possible to envision a future wherein the net total for soil sequestration averages higher than recent levels. This comes with one caveat, however: as noted, a shift toward perennials implies increased cattle numbers—emissions from which could exceed any tonnages from sequestration. Note how, in Figure 3, category 1c (area of annual vs. perennial crops) and 2a (enteric emissions from cattle) move as mirror images to each other; they appear to be inversely related. Because of complex interdependencies, solutions in one place can create problems in another. A systems approach is needed.

Sources: Sum of preceding six categories: 1a, 1b, 1c, 1d, 1e, and 1f.

Emission categories

All the following categories represent emissions of one or more of the three main GHGs: N_2O, CH_4, or CO_2. All numbers are positive: they represent releases into the atmosphere. All categories are represented in a stacked area graph in Figure 3 wherein the top line, 83.2 Mt CO_2e in 2020, is the sum of the 34 emissions bands that comprise it. (Note that there are 41 categories in Figure 3: 34 for emissions and 7 for soil-atmosphere exchanges.) The following categories cover emissions from livestock, fertilizer use, input production, on-farm energy use, etc.

2a. Enteric emissions, beef cattle

Methane; 19.0 Mt CO_2e/y in 2020 (uncertainty range 16.0–23.0 Mt[44]); 22.8% of Cdn. ag. emissions

Unlike many animals, cattle and other ruminants can digest grass, forage, and other materials high in cellulose and related compounds. This is possible because these animals have multiple stomachs that host symbiotic bacteria that break down these compounds. A byproduct of this bacterial metabolism is methane (CH_4), a GHG roughly 30 times more powerful than CO_2 in its capacity to trap atmospheric heat.[45] Beef cattle produce 79 percent of total enteric methane emissions and dairy cattle 15 percent, for a total of 94 percent. Emissions from sheep, goats, and other ruminants make up the residual. Enteric emissions from beef cattle peaked in 2005, came down as herd size decreased, and stabilized somewhat since 2010.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC, on request). See *NIR 2022*, Part 1, section 5.2.

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[44] Uncertainty ranges can be found throughout ECCC, NIR, Part 1, Ch. 5, and elsewhere.

[45] Global Warming Potential (GWP) compares the effect of GHGs such as methane or nitrous oxide to the same weight of carbon dioxide. In the present report's text, in order to make things easy to remember and to provide approximate indications of the relative effects of GHGs, we say that methane is about 30 times stronger than CO_2 and nitrous oxide is about 300 times stronger. But the actual emission tonnage numbers in this report, mostly provided by ECCC, use *precise* GWP_{100} values: N_2O = 298 (IPCC AR4) or 265 (AR5); CH_4 = 25 (AR4) or 28 (AR5).

2b. Enteric emissions, dairy cattle

Methane; 3.5 Mt CO_2e/y in 2020 (uncertainty range 2.9–4.2 Mt); 4.2% of Cdn. ag. emissions

Emissions fell during the period 1990 to 2007, then stabilized, but have been increasing since 2016. In general, the number of dairy cattle is falling, but emissions per animal are rising for reasons related to increased per-animal production, feed consumption, etc.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC, on request). See *NIR 2022*, Part 1, section 5.2.

2c. Manure management, beef cattle

Methane and nitrous oxide; 3.2 Mt CO_2e/y in 2020 (uncertainty range approx. ±50%); 3.8% of Cdn. ag. emissions

Common manure-management systems include liquid storage; solid/drylot; and pasture/paddock. Composting systems and biodigesters are rare in Canada. Both methane and nitrous oxide are emitted during manure storage, handling, and application. In general, liquid or poorly aerated manure emits predominantly methane while dry, aerated systems generate mostly nitrous oxide. Most beef cattle manure is handled dry. Since 2005, emissions from beef cattle manure have fallen as animal numbers have fallen.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.3.

2d. Manure management, dairy cattle

Methane and nitrous oxide; 1.2 Mt CO_2e/y in 2020 (uncertainty range approx. ±50%); 1.5% of Cdn. ag. emissions.

Emissions trendline is upward.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.3.

2e. Enteric emissions, other livestock

Methane; 1.1 Mt CO_2e/y in 2020 (uncertainty range 0.9–1.2 Mt); 1.3% of Cdn. ag. emissions

“Other livestock” includes bison, sheep, llamas, alpacas, horses, goats, elk, deer, wild boars, foxes, minks, rabbits, swine, boars, and mules and asses.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.2.

2f. Manure management, swine

Methane and nitrous oxide; 1.8 Mt CO_2e/y in 2020 (uncertainty range approx. ±50%); 2.1% of Cdn. ag. emissions

Most hog manure is handled in liquid form, thus emitting predominantly CH_4. Emissions trendline is up and down and then up again, with peaks in the early 2000s and again in recent years.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.3.

2g. Manure management, poultry

Methane and nitrous oxide; 0.8 Mt CO_2e/y in 2020 (uncertainty range approx. ±50%); 1.0% of Cdn. ag. emissions

Most poultry manure is handled dry, therefore emissions are mostly N_2O. Emissions are rising.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.3.

2h. Manure management, other livestock

Methane and nitrous oxide; 0.2 Mt CO_2e/y in 2020 (uncertainty range approx. ±50%); 0.2% of Cdn. ag. emissions

This category captures manure emissions from bison, goats, horses, sheep, llamas/alpacas, foxes, mink, rabbits, deer/elk, and wild boars.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.3.

2i. Manure management, indirect emissions

Nitrous oxide; 0.6 Mt CO_2e/y in 2020 (uncertainty range approx. ±50%); 0.6% of Cdn. ag. emissions

ECCC explains indirect emissions: "A fraction of the nitrogen in manure that is stored is transported off-site through volatilization in the form of NH_3 [ammonia] and NO_x [nitrogen oxides] and subsequent redeposition. Furthermore, solid manure exposed to rainfall will be prone to loss of N through leaching and runoff. The nitrogen that is transported from the manure storage site in this manner is assumed to undergo subsequent nitrification and denitrification elsewhere in the environment and ... to produce N_2O."[46]

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.3.

3a. Soils, synthetic nitrogen fertilizer, direct

Nitrous oxide; 8.5 Mt CO_2e/y in 2020 (uncertainty range 5.5–12.2 Mt); 10.2% of Cdn. ag. emissions

When nitrogen fertilizer is applied to soils, the actions of bacteria (nitrification and denitrification) and other reactions release some of that nitrogen as nitrous oxide (N_2O), a GHG approximately 300 times more powerful than carbon dioxide in terms of trapping atmospheric heat. This emissions category is among the largest, second only to enteric emissions from beef cattle. Moreover, the trendline is sharply upward—having more than doubled since 1990 as a result of increasing fertilizer application rates and tonnage.

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[46] Environment and Climate Change Canada, "NIR 2021 Part 1," 128.

This category—direct soil emissions from the use of nitrogen fertilizer—includes only one aspect of nitrogen-fertilizer-related emissions. Other emissions from nitrogen fertilizer use and production are included in the following six categories: 3b. Soils, synthetic nitrogen fertilizer, indirect; 3c. Soils, urea nitrogen fertilizer application; 3d. Soils, other carbon-containing fertilizers; 3e. Input manufacture, nitrogen fertilizer; 3f. Input manufacture, nitrogen fertilizer, natural gas; and 3g. Input manufacture, nitrogen fertilizer, transport.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.4.

Note 1: The values used for this category, "Soils, synthetic nitrogen fertilizer, direct," take into account (i.e., subtract, or are net of) the negative values recorded in another ECCC category: "Changes in N_2O emissions from adoption of no-till and reduced tillage." This latter category is a negative adjustment to N_2O emissions of about 2.5 Mt in 2020, negating 23 percent of nitrogen-fertilizer-related direct soil emissions in that year. This latter category is detailed in NIR Part 1, Table 5-7 and section 5.4.1.7, where ECCC explains: "Compared with conventional or intensive tillage, the practice of direct seeding or no-tillage, as well as reduced tillage, results in changes to several factors that influence N_2O production, including decomposition of soil organic matter, soil carbon and nitrogen availability, soil bulk density, and water content.... As a result, compared with conventional tillage, conservation tillage ... generally reduces N_2O emissions for the Prairies ... but increases N_2O emissions for the non-Prairie regions of Canada.... The net result across the country is a small reduction in emissions. ... This reduction is reported separately as a negative estimate ... to preserve the transparency in reporting."[47] Though transparency is important, to make the Figure 3 graph legible, rather than including this as a separate emissions category (with counterintuitive *negative* values), instead we subtract this category of negative values from the large quantity of direct N_2O emissions from nitrogen fertilizer use (i.e., category 3a).

ECCC also quantifies and reports other adjustments to soil N_2O emissions such as adjustments for irrigation (see category 5g, below). Because those values are positive rather than negative, they can be shown as separate categories in the Figure 3 graph.

Sources: See *NIR 2022*, Part 1, section 5.4.1.7.

Note 2: Large uncertainties—several Mt CO_2e per year—surround emissions from nitrogen fertilizer use. For a given tonne of fertilizer, emissions vary based on rate, time of application, fertilizer placement (e.g., surface spread versus deep banded), formulation/source, soil texture and type, soil moisture, precipitation and temperature following application, whether farmers take special measures to reduce emissions (e.g., variable rate or split application), seeding date, crop grown, yield, use of cover crops, etc. Moreover, emissions appear to be non-linear with, for example, a 10 percent increase in rates leading to an increase in emissions of more than 10 percent.[48] Despite these uncertainties, we know that emissions related to nitrogen fertilizer use are among the largest from agriculture and that they are rising rapidly.

Note 3: Throughout this report, units for fertilizer nitrogen are tonnes of actual nitrogen nutrient, not tonnes of fertilizer product (e.g., urea, 46-0-0, is 46 percent actual nitrogen by weight). This report attempts to be consistent in using "fertilizer nitrogen" and "nitrogen in fertilizer" when talking about

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[47] "NIR 2022 Part 1," 162.

[48] Yu Jiang et al., "Nonlinear Response of Soil Ammonia Emissions to Fertilizer Nitrogen," *Biology and Fertility of Soils* 53, no. 3 (April 2017); Dong-Gill Kim, Guillermo Hernandez-Ramirez, and Donna Giltrap, "Linear and Nonlinear Dependency of Direct Nitrous Oxide Emissions on Fertilizer Nitrogen Input: A Meta-Analysis," *Agriculture, Ecosystems & Environment* 168 (March 15, 2013); Iurii Shcherbak, Neville Millar, and G. Philip Robertson, "Global Metaanalysis of the Nonlinear Response of Soil Nitrous Oxide (N2O) Emissions to Fertilizer Nitrogen," *Proceedings of the National Academy of Sciences* 111, no. 25 (June 24, 2014).

quantities/tonnage, but it uses the more generic “nitrogen fertilizer” when referring to the substance. Again, unless otherwise noted, quantities are tonnes of *actual N nutrient*, not product.

3b. Soils, synthetic nitrogen fertilizer, indirect

Nitrous oxide; 2.3 Mt CO_2e/y in 2020 (uncertainty range approx. −75% to +100%); 2.7% of Cdn. ag. emissions

When applied to agricultural soils, synthetic nitrogen fertilizers emit greenhouse gases not only directly but also indirectly. The latter occurs off-site, after non-GHG nitrogen compounds have moved through air (volatilization) or water (leaching into groundwater or runoff into surface waters). According to ECCC, “Indirect emission[s] occur through two pathways: (1) the volatilization of nitrogen [as NH_3, NO_x, etc.] from inorganic fertilizer and manure applied to fields ... and its subsequent deposition off-site; and (2) the leaching and runoff of inorganic fertilizer, manure and crop residue N.”[49] ECCC goes on to detail that the “quantity of ... volatilized nitrogen depends on a number of factors, such as rates of fertilizer and manure nitrogen application, fertilizer types, methods and time of nitrogen application, soil texture, rainfall, temperature, and soil pH.”[50] In some cases, such as leaching of nitrogen into groundwater, the eventual production of N_2O may be separated from fertilizer application by tens of kilometres and by years or even decades.[51] Fertilizer run-off can cause emissions in far-off rivers or even in ocean “dead zones.” Although ECCC reporting of indirect emissions attempts to account for all these off-site emissions, some gaps may exist. Stated another way: the uncertainty range may be large.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 contains values for “Agricultural soils, indirect sources.” Upon request, ECCC subdivided this data for indirect emissions into four subcategories: inorganic nitrogen fertilizers; organic nitrogen fertilizers; crop residue decomposition; and manure on pasture, range, and paddock.

3c. Soils, urea nitrogen fertilizer application

Carbon dioxide; 2.5 Mt CO_2e/y in 2020 (uncertainty range ±1.2 Mt); 3.0% of Cdn. ag. emissions

In a process that involves adding carbon dioxide (CO_2) to ammonia (NH_3), fertilizer companies manufacture urea: $(NH_2)_2CO$. Natural gas (CH_4) is the usual source for the CO_2—a byproduct of the process for obtaining hydrogen (H) for ammonia (NH_3) production. More than 40 percent of Canadian fertilizer-production CO_2 is captured and used to make urea,[52] with much of the rest vented from fertilizer factories as a GHG (see category 3e). That CO_2 in urea, originally from fossil fuel natural gas, is later released from the soil as the fertilizer breaks down. This equation shows the reaction:

$$(NH_2)_2CO + H_2O \rightarrow NH_4^+ + OH^- + CO_2$$

Emissions in this category are rising as fertilizer rates increase and a greater portion of fertilizer is applied as urea. 2020 levels were more than triple those in 1990.

Sources: ECCC, “Canada. 2022 Common Reporting Format (CRF) Table,” UNFCCC Documents, accessed May 15, 2022, https://unfccc.int/documents/461923, Table 10s1. See also *NIR 2022*, Part 1, section 5.7.

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[49] Environment and Climate Change Canada, “NIR 2021 Part 1,” 129.

[50] Environment and Climate Change Canada, "NIR Part 1," 137.

[51] M. Sebilo et al., “Long-Term Fate of Nitrate Fertilizer in Agricultural Soils,” *Proceedings of the National Academy of Sciences* 110, no. 45 (2013).

[52] Natural Resources Canada and Canadian Fertilizer Institute, “Canadian Ammonia Producers: Benchmarking Energy Efficiency and Carbon Dioxide Emissions” (Ottawa: NRCan, 2008), 13.

3d. Soils, other carbon-containing fertilizers

Carbon dioxide; 0.3 Mt CO_2e/y in 2020 (uncertainty range unknown); 0.4% of Cdn. ag. emissions

As its name implies, urea-ammonium nitrate (UAN) is a solution containing urea and thus it contains carbon. This category reports the CO_2 released in the field from the C in UAN. Again, the original source for that C (and CO_2) is natural gas (CH_4).

Sources: ECCC, "Canada. 2022 Common Reporting Format (CRF) Table," UNFCCC Documents, accessed May 15, 2022, https://unfccc.int/documents/461923, Table 10s1.

3e. Input manufacture, nitrogen fertilizer

Primarily carbon dioxide, some nitrous oxide, and perhaps some methane; 7.5 Mt CO_2e/y in 2020 (uncertainty range moderate); 9.0% of Cdn. ag. emissions

Briefly, emissions from nitrogen fertilizer production facilities consist primarily of:

1. CO_2 from ammonia (NH_3) production from: A. combustion of natural gas to produce needed heat, pressures, and steam; and B. venting excess CO_2 from the process of splitting methane (CH_4) to produce the hydrogen (H) needed for ammonia (NH_3); and
2. Nitrous oxide (N_2O) from nitric acid (HNO_3) production. Nitric acid is used to produce certain fertilizers including ammonium nitrate (AN) and urea ammonium nitrate (UAN).

There may also be emissions from methane leakage at production facilities (see Haridy and Zhou et al. footnote below), but data is inadequate to quantify and include such flows at this time.

One could do an entire report on fertilizer production emissions; many have.[53] Here, however, is a concise explanation of the NFU's methodology for calculating emissions from the production of Canadian farmers' nitrogen fertilizer supply:

1. Based on several studies (see Table 5) but drawing most directly from Brentrup et al.,[54] we chose an emissions coefficient for nitrogen fertilizer production: 2.8 tonnes CO_2e per tonne of actual N nutrient in the fertilizer applied by farmers;
2. We applied this coefficient for 2014 (the year for which Brentrup et al. derive their numbers);
3. We made an annual adjustment for the years before and after 2014, as follows: Fertilizer plants have been achieving higher efficiency (lower energy use and emissions per tonne of N) year after year so it is logical to assume that emissions per tonne fall as we move forward in time. In addition, as we move forward in time from 1990, we see that a greater portion of Canadian fertilizer use has been in the form of urea and UAN,[55] thus an increasing proportion of CO_2 has

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[53] Stefano Menegat, Alicia Ledo, and Reyes Tirado, "Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers in Agriculture," preprint (Research Square, October 22, 2021); A. Kool, M. Marinussen, and H. Blonk, "LCI Data for the Calculation Tool Feedprint for Greenhouse Gas Emissions of Feed Production and Utilization: GHG Emissions of N, P and K Fertilizer Production" (Gouda, Netherlands: Blonk Consultants, 2012), http://www.blonkconsultants.nl/wp-content/uploads/2016/06/fertilizer_production-D03.pdf; Blonk Consultants and Nicolo' Braconi, "Updated Fertilizer Production in Agri-Footprint: Life Cycle Inventories & Carbon Footprint Results" (Gouda, NL: Agri-Footprint, 2020); International Fertilizer Industry Association, "Fertilizers, Climate Change and Enhancing Agricultural Productivity Sustainability" (Paris: IFA, 2009); Jessica Bellarby et al., "Cool Farming: Climate Impacts of Agriculture and Mitigation Potential" (Amsterdam: Greenpeace, 2008); Frank Brentrup et al., "Updated Carbon Footprint Values for Mineral Fertilizer from Different World Regions" (11th International Conference on Life Cycle Assessment of Food 2018, Bangkok, 2018); Antione Hoxha and Bjarne Christensen, *The Carbon Footprint of Fertiliser Production: Regional Reference Values*, Proceedings / International Fertiliser Society 805 (Colchester: International Fertiliser Society, 2019).

[54] Brentrup et al., "Updated Carbon Footprint Values for Mineral Fertilizer from Different World Regions."

[55] Stats Can Tables 32-10-0038-01 and 32-10-0273-01. Urea and UAN have gone from approximately half of nitrogen fertilizer product tonnage to approximately three-quarters. Note that the analysis here is incomplete (e.g., tonnes of product vs tonnes of N) and a thorough analysis of emissions associated with on-farm fertilizer use cannot be completed without additional data from fertilizer producers. As we note elsewhere, this analysis should be conducted and published by ECCC. Publicly available data at this time allows only estimates. That said, the magnitude of emissions is not in doubt: several million tonnes per year.

been diverted away from atmospheric release and into urea and UAN production (and hence emitted later from in-field urea lysis, and recorded in categories 3c and 3d). Based on several factors (though lacking in precision due to lack of data), we have estimated these factors together as leading to a change in emissions intensity of 1.2 percent per year. Again: Based on Brentrup and others, we chose an emissions coefficient of 2.8 tonnes CO_2e for 2014, but with the 1.2 percent per annum change/reduction in emissions intensity the emission factor for 2020 works out to 2.60 and for 1990 is 3.73. In effect, we are modelling a 30 percent reduction in emissions intensity (tonnes CO_2e per tonne of N) over the 1990 to 2020 period.

4. For each year (1990 to 2020, inclusive) we multiplied that year's emissions coefficient times farmers' consumption of fertilizer nitrogen tonnage (Stats Can Tables 32-10-0039-01 and 32-10-0274-01).[56]

To assess the accuracy of our emissions numbers, we compared them to values from Dyer et al., Menegat et al. (preprint), the IFA, Brentrup et al., Hoxha and Christensen, and others. See Table 5.

Several issues remain for future research and refinements to nitrogen production coefficients, including:

A. Future effects of carbon capture, use, and storage (CCUS) (e.g., Nutrien's Redwater, Alberta, plant);
B. N_2O emissions from nitric acid production and the installation of N_2O abatement technologies (some sources note that Canadian nitrogen fertilizer producers have lower N_2O emissions from nitric oxide production than do US producers, but because most sources list only North American coefficients, refinements are needed in future editions of these calculations);
C. Published reports that methane emissions (i.e., natural gas leakage) at nitrogen fertilizer production facilities may be 100 times higher than reported;[57]
D. Effects of increasingly stringent methane emission restrictions, e.g., Canada's commitment to cut CH_4 emissions by 75 percent;
E. General pressures on all manufacturers as Canada moves toward 2030 and 2050 emission reduction commitment deadlines; and
F. Perhaps increasingly stringent restrictions under Canada's Output Based Pricing System (OBPS) which may in the future impose emissions costs on fertilizer makers, though, currently, those emissions are almost wholly exempted from OBPS charges.

Sources: Methodology and calculation by NFU based on published sources. See Table 5, below, and explanation of methodology, above.

Note 1: For fertilizers, farm machinery, and all other farm inputs, our calculations are for the emissions from the inputs *actually used* on Canadian farms, not for the quantities of those inputs produced in Canada. Imports and exports can cause Canadian production and consumption to diverge, especially for inputs such as farm machinery and potassium and phosphorus fertilizers.

Note 2: There is a pressing need to better understand N_2O emissions from the production of nitric acid (HNO_3), the magnitude of CH_4 emissions from the fertilizer factories themselves, and CO_2 emissions from the production process. As a valuable contribution to understanding food system GHG production, it is strongly recommended that ECCC quantify and report all aspects of nitrogen fertilizer production emissions, in aggregate and on a product-specific per-tonne-of-N basis for each year from 1990 to present.

3f. Input manufacture, nitrogen fertilizer, upstream natural gas supply

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[56] In future editions, for each year, separate emissions factors could be applied to the tonnage of each fertilizer type used on Canadian farms and those emissions from each type of fertilizer production could be summed to give total for the production of all fertilizer used on Canadian farms.

[57] Rich Haridy, "Startling Study Finds US Fertilizer Industry Emits 100 Times More Methane than Estimated," New Atlas, June 7, 2019, https://newatlas.com/fertilizer-methane-emissions-100-times-higher/60029/; Xiaochi Zhou et al., "Estimation of Methane Emissions from the U.S. Ammonia Fertilizer Industry Using a Mobile Sensing Approach," *Elem Sci Anth* 7, no. 1 (2019).

Methane and carbon dioxide; 0.9 Mt CO_2e/y in 2020 (uncertainty range very high); 1.1% of Cdn. ag. emissions

The preceding emissions category for nitrogen fertilizer production encompasses emissions *at the production facility*: mostly CO_2 from the combustion of natural gas and CO_2 vented after hydrogen (H) has been harvested from the natural gas methane (CH_4). But natural gas is itself a product and has upstream production and processing emissions. Gas wells must be drilled, reservoirs often must be fracked, and gas must be processed and pumped. That industrial activity creates CO_2 and other emissions—from trucks, drill rigs, compressors, etc. Also, a significant amount of CH_4 (and some CO_2) leaks or is vented—releasing so-called "fugitive" emissions. The emissions category here, "Input manufacture, nitrogen fertilizer, upstream natural gas supply," sums those upstream CH_4 and CO_2 emissions and reports them as CO_2e. For more on upstream natural gas emissions as they pertain to fertilizer production, see Kool et al.[58]

Data for emissions from upstream natural gas production and processing includes large uncertainties and gaps. One study from the US says that "analyses are weakened by the paucity of empirical data addressing CH_4 emissions through the natural gas supply network."[59] A 2021 Canadian study comes to the same conclusion, stating that "drivers of ... emissions in Alberta (AB) and British Columbia (BC) from the NG industry are poorly understood, and reported data are insufficient to inform policy and target emissions reduction."[60] Thus, there are limits to our ability to quantify these emissions. In this report, we adopt a simplified methodology that stays close to ECCC data. There are good reasons, however, to believe that upstream natural gas emissions are underreported. For this category, one can think of the emissions value we derive below and depict in the Figure 3 graph as a placeholder—to be refined in the future.

To calculate the upstream emissions for the natural gas used to make Canadian farmers' nitrogen fertilizer we utilized the following methodology:

> Total upstream emissions for natural gas production and processing (combustion and fugitive) in Canada in 2019 (ECCC, tonnes CO_2e)
> ÷ total natural gas production in Canada in 2019 (Stats Can, gigajoules)
> x quantity of gas needed to produce one tonne of fertilizer nitrogen (NRCan, gigajoules/tonne)
> x the tonnes of nitrogen in fertilizer used by Canadian farmers in 2020 (Stats Can, tonnes per year).

Putting values to this methodology, we derive the following:

> 52.7 Mt CO_2e per year in upstream emissions from natural gas production and processing[61]
> ÷ 6.94 billion gigajoules (GJ) of natural gas produced
> x 40 GJ natural gas per tonne of actual N produced
> x 2.9 million tonnes of fertilizer nitrogen

See details and sources for numbers below.

Note that average upstream emissions per unit of natural gas have fluctuated over the past 30 years and will change in the future as governments work with energy companies to reduce methane emissions. Our calculations use a constant emissions factor for all years, based on calculations for 2019. Year-by-year

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[58] A. Kool, M. Marinussen, and H. Blonk, "LCI Data for the Calculation Tool Feedprint for Greenhouse Gas Emissions of Feed Production and Utilization: GHG Emissions of N, P and K Fertilizer Production" (Gouda, NL: Blonk Consultants, 2012).

[59] Ramón A. Alvarez et al., "Greater Focus Needed on Methane Leakage from Natural Gas Infrastructure," *Proceedings of the National Academy of Sciences* 109, no. 17 (April 24, 2012).

[60] Ryan E. Liu et al., "Greenhouse Gas Emissions of Western Canadian Natural Gas: Proposed Emissions Tracking for Life Cycle Modeling," *Environmental Science & Technology* 55, no. 14 (July 20, 2021).

[61] Emissions from transmission and distribution, though much smaller (see Table 4), could also be included. We have chosen not to because we were unable to discern what portion of these emissions might be related to the large-capacity industrial distribution system versus the more fine-veined urban/residential systems.

emissions factors should be calculated for future editions of this report.[62] Nonetheless, figures here almost certainly underestimate actual emissions.

ECCC reports 52.7 Mt of upstream emissions for natural gas production and processing in 2019.[63] The screen capture below is excerpted from an ECCC Table.[64]

Table 4. Upstream emissions from natural gas production and processing.

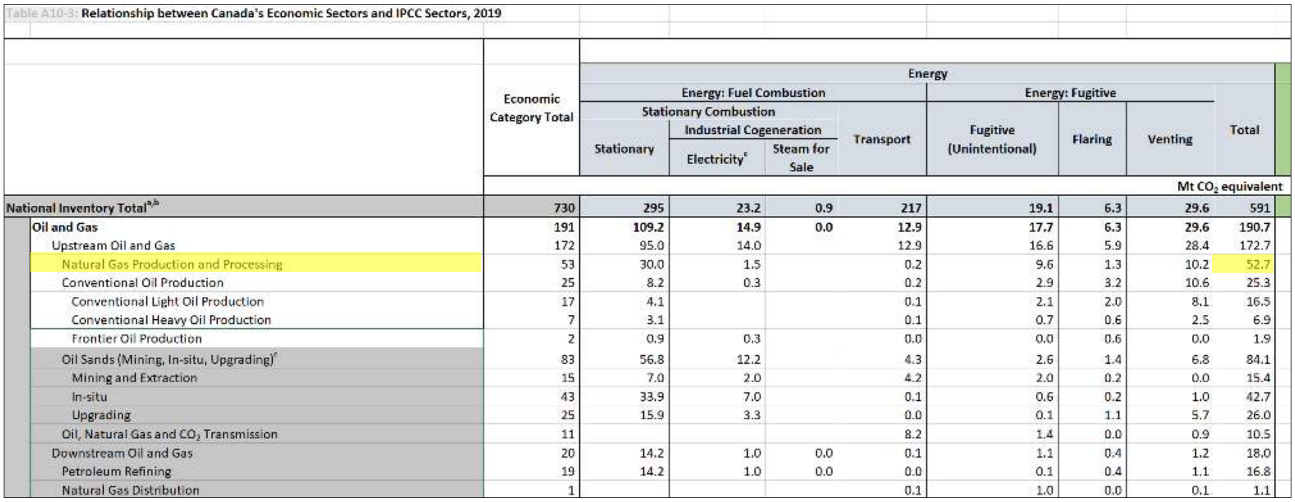

Table A10-3: **Relationship between Canada's Economic Sectors and IPCC Sectors, 2019**

	Economic Category Total	Energy								
		Energy: Fuel Combustion				Energy: Fugitive			Total
		Stationary Combustion			Transport	Fugitive (Unintentional)	Flaring	Venting	
		Stationary	Industrial Cogeneration						
			Electricity[c]	Steam for Sale					
									Mt CO_2 equivalent
National Inventory Total[a,b]	**730**	**295**	**23.2**	**0.9**	**217**	**19.1**	**6.3**	**29.6**	**591**
Oil and Gas	**191**	**109.2**	**14.9**	**0.0**	**12.9**	**17.7**	**6.3**	**29.6**	**190.7**
Upstream Oil and Gas	172	95.0	14.0		12.9	16.6	5.9	28.4	172.7
Natural Gas Production and Processing	53	30.0	1.5		0.2	9.6	1.3	10.2	52.7
Conventional Oil Production	25	8.2	0.3		0.2	2.9	3.2	10.6	25.3
Conventional Light Oil Production	17	4.1			0.1	2.1	2.0	8.1	16.5
Conventional Heavy Oil Production	7	3.1			0.1	0.7	0.6	2.5	6.9
Frontier Oil Production	2	0.9	0.3		0.0	0.0	0.6	0.0	1.9
Oil Sands (Mining, In-situ, Upgrading)[c]	83	56.8	12.2		4.3	2.6	1.4	6.8	84.1
Mining and Extraction	15	7.0	2.0		4.2	2.0	0.2	0.0	15.4
In-situ	43	33.9	7.0		0.1	0.6	0.2	1.0	42.7
Upgrading	25	15.9	3.3		0.0	0.1	1.1	5.7	26.0
Oil, Natural Gas and CO_2 Transmission	11				8.2	1.4	0.0	0.9	10.5
Downstream Oil and Gas	20	14.2	1.0	0.0	0.1	1.1	0.4	1.2	18.0
Petroleum Refining	19	14.2	1.0	0.0	0.0	0.1	0.4	1.1	16.8
Natural Gas Distribution	1				0.1	1.0	0.0	0.1	1.1

Source: Reproduced from ECCC emissions tables.[65]

Note: Yellow-highlighted line indicates the category referenced in this report. Other categories and values are not used.

Again, several studies in Canada and the US that used direct gas measurement to attempt to quantify actual emissions over the long term and over large spatial areas concluded that numbers such as those reported by ECCC and the US EPA may be well below actual emissions. A 2021 article is entitled "Methane Emissions from Upstream Oil and Gas Production in Canada Are Underestimated."[66] A 2020 article is entitled "Eight-Year Estimates of Methane Emissions from Oil and Gas Operations in Western Canada are Nearly Twice Those Reported in Inventories."[67] (Note: These articles deal with methane emissions, whereas overall emissions from upstream natural gas production include methane *and* carbon dioxide.)

Using ECCC figures, upstream production and processing emissions for natural gas in Canada were 52.7 Mt CO_2e in 2019.[68] Canadian "marketable production" of natural gas in 2019 was 6.94 billion gigajoules (GJ).[69]

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[62] Table A10-2 of the NIR provides total emissions from natural gas production and processing for each year and this could form the basis for year-by-year emissions values.

[63] See the ECCC website for Canadian GHG emissions reporting, for both IPCC Sectors and Economic Sectors. Content is formatted as spreadsheets. See ECCC, "Home - Environment and Climate Change Canada Data," accessed January 19, 2022, https://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/B-Tables-Canadian-Economic-Sector-Canada/?lang=en.

[64] Upon inquiry, ECCC explained that the 52.7 Mt figure "includes all emissions associated with the exploration, extraction, gathering and processing of natural gas from the producing reservoir to the transmission pipeline. This includes emissions from combustion (e.g., in compressors), flaring, venting, and leaks. It does not include the emissions associated with the transmission, storage or distribution of the natural gas or the end-use combustion or feedstock use of natural gas."

[65] ECCC, "Home-Environment and Climate Change Canada Data," accessed January 19, 2022, https://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/B-Tables-Canadian-Economic-Sector-Canada/?lang=en.

[66] Katlyn MacKay et al., "Methane Emissions from Upstream Oil and Gas Production in Canada Are Underestimated," *Scientific Reports* 11, no. 1 (April 13, 2021).

[67] Elton Chan et al., "Eight-Year Estimates of Methane Emissions from Oil and Gas Operations in Western Canada Are Nearly Twice Those Reported in Inventories," *Environmental Science & Technology* 54, no. 23 (December 1, 2020).

[68] The 2021 NIR notes that these numbers and methodologies are under revision as part of ongoing work to refine reported values.

[69] Statistics Canada Table 25-10-0055-01.

Dividing the first number by the second reveals upstream emissions of 0.0076 tonnes CO_2e per GJ of natural gas. This value aligns with, and is at the low end of, a range of published values.[70]

Fertilizer production requires approximately 33 GJ of natural gas per tonne of ammonia (NH_3).[71] Because NH_3 is 82 percent N, this equates to 40 GJ per tonne of actual N. Multiplying 0.0076 tonnes CO_2e per GJ of natural gas times 40 GJ natural gas per tonne of N yields a figure for upstream natural gas emissions per tonne of fertilizer nitrogen produced: 0.304 tonnes CO_2e per tonne of nitrogen in fertilizer. Multiplying this last figure by farmers' fertilizer consumption in 2020, 2.9 million tonnes of fertilizer nitrogen, gives us a value for total emissions for upstream natural gas attributable to Canadian fertilizer use: 0.88 Mt CO_2e. Again, actual emissions may be much higher, but it is important to include some quantity here, if only as a placeholder for future calculations that can draw upon more complete data.

We performed the following error-check against our calculated value. Natural Resources Canada (NRCan) tells us that "the fertilizer industry consumes about 8 percent of the natural gas used in Canada."[72] As noted, ECCC quantifies upstream emissions from natural gas production and processing at 52.7 Mt (Table 4). Multiplying 8 percent times 52.7 Mt equals 4.2 Mt. This figure would represent annual GHG emissions from the production of the natural gas used in Canadian fertilizer production facilities in 2019. Note that this 4.2 Mt is *much* higher than the 0.88 Mt figure we have adopted. Part of the difference is explained by the fact that Canada exports some of its nitrogen fertilizer, such that emissions from Canadian production will not match emissions from Canadian consumption. Nonetheless, this error-check calculation indicates that a more in-depth analysis of this emissions category would probably result in a much higher figure.

Sources: Methodology and calculation by NFU based on published sources. See Table 5, below, and explanation of methodology, above.

3g. Input manufacture, nitrogen fertilizer, transport

Mostly carbon dioxide; 0.2 Mt CO_2e/y in 2020 (uncertainty range very high); 0.2% of Cdn. ag. emissions

There are few values for emissions from nitrogen fertilizer transport in Canada—either by rail or truck. Menegat et al. (preprint) estimate emissions at 0.7 Mt per year—equal to 1.9 percent of the total they calculate for all emissions from nitrogen fertilizer production and use in Canada.[73] Compared to that 1.9 percent figure, the International Fertilizer Agency (IFA) estimates that, globally, transport emissions are 3.5 percent of total emissions from nitrogen production and use (Table 5). We believe these estimates are too high. Based on limited data, we calculated transport-related emissions at 0.17 Mt in 2020, based on the following scenario:

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[70] 0.0076 tonnes CO_2e per GJ of natural gas is equivalent to 7.6 grams CO_2e per MJ of natural gas. A literature review contained in a 2021 article by Liu et al lists several upstream emissions estimates in terms of grams CO_2e per MJ. Those values include several in the range of 6 to 7 grams CO_2e per MJ natural gas, but also many much higher from Canada and the US, ranging from 8 to 23 grams per MJ. Our value of 7.6 grams aligns well with the values provided. Liu et al report a "current best estimates of British Columbia (BC) emissions intensities of 6.2−12 g CO_2e/MJ NG and a US average estimate of 15 g CO_2e/MJ" See Ryan Liu et al., "Greenhouse Gas Emissions of Western Canadian Natural Gas: Proposed Emissions Tracking for Life Cycle Modeling," *Environmental Science & Technology* 55, no. 14 (July 20, 2021).

[71] Natural Resources Canada and Canadian Fertilizer Institute, "Canadian Ammonia Producers: Benchmarking Energy Efficiency...." See also Vaclav Smil, *Energy in Nature and Society: General Energetics of Complex Systems* (Cambridge, MA: MIT Press, 2007), p. 286.

[72] Natural Resources Canada and Canadian Fertilizer Institute, 3.

[73] Menegat, Ledo, and Tirado, "Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers...."

Trucking emissions of 60 grams CO_2e per tonne-km[74]
x 500 km average round trip from production facility, to distribution, to farm, and, in some cases, empty return trip (versus loaded backhaul)[75]
x 2020 nitrogen fertilizer product tonnage of 5.8 million[76]

As a check on our figure: 5.8 million tonnes x 350 kms (distance adjusted for potential empty backhauls) = 2.0 billion tonne-kms—a number approximately two-thirds-of-one percent of total Canadian truck transport tonne-kms.[77] ECCC reports that emissions from heavy-duty diesel vehicles totaled 51.8 Mt CO_2e in 2019.[78] Two-thirds-of-one percent of that figure is 0.35 Mt CO_2e, approximately double our estimate of 0.17 Mt CO_2e.

Little data is available. There is a need for research to refine this number and to obtain detailed numbers regarding rail and truck transport of Canadian farmers' nitrogen fertilizer supplies. But since it is a small part of fertilizer-related emissions, future refinements are unlikely to have policy or climate implications.

Sources: Methodology and calculation by NFU based on published sources. See Table 5, below, and explanation of methodology, above.

Nitrogen fertilizer, summary and sources

Table 5, below, collects various emissions values, lists comparables, and provides sources.

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[74] Natural Resources Canada, "SmartWay Tools and Resources: Carrier-Emissions-Rankings-Results" (Natural Resources Canada, May 1, 2018), https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/greening-freight-programs/smartway-fuel-efficient-freight-transportation/carrier-emissions-rankings-results/carrier-emissions-rankings-results/21078.

[75] No data is available on average length of haul distances for fertilizer or, perhaps more important, for backhaul utilization. Depending on backhauls, this 500 km estimate may be too high. That said, this is a small component of overall emissions related to fertilizer use, i.e., total nitrogen-fertilizer-related emissions are not sensitive to haul-distance estimates.

[76] Note that this is twice the value for fertilizer tonnage used elsewhere in this report (2.9 million tonnes fertilizer nitrogen). This 2x adjustment has been made because the weight of nitrogen fertilizer is far higher than that of just the weight of the nitrogen in the fertilizer. For example, urea is 46% N by weight, and UAN is just 28% N (i.e., the fertilizer weighs nearly 4 times the N content). This 2x adjustment is a rough multiplier and may underestimate the case.

[77] Statistics Canada Table 23-10-0219-01.

[78] Environment and Climate Change Canada, "NIR 2021 Part 1," Table 3-8.

Table 5. Emissions values for nitrogen-fertilizer-related categories, various sources.

	Global		**Canada**					**N. America**		**Canada**
	Menegat et al.[79] (for 2018)	Int'l Fert Agency (IFA)[80] (for 2006 & '07)	Menegat et al. (for 2018)	Dyer et al. (for 2014)[81]	ECCC NIR[82] (for 2020)	NRCAN and CFI[83] (for 2002)	Cheminfo/ Cdn Round Table (2016)[84]	Hoxha and Christensen[85] (for 2013-'16)	Brentrup et al.[86] (for 2014)	**NFU** **(for 2020)**
Use, in-field/direct (N_2O) (Mt CO_2e/y) [3a]	379.9 ±160.5 (30.5%)	604.6 n.a. (56.5%)	15.3 ±54.5 (42.6%)	--	8.5* -3.0/+3.7 (--)	--		--	--	**8.5*** **-3.0/+3.7** **(38.3%)**
Use, indirect, volatilization (N_2O) (Mt CO_2e/y) [3b]	105.1 ±26.6 (8.4%)	Incl. in top category	2.8 ±2.0 (7.8%)	--	2.3 Unknown (--)	--		--	--	**2.3** **(10.4%)**
Use, indirect, leaching (N_2O) (Mt CO_2e/y)	206.2 ±72.1 (16.6%)	Incl. in top category	5.9 ±5.7 (15.4%)	--	Incl. in prev.	--		--	--	**Incl. in prev.**
Use, in-field, from urea (CO_2) (Mt CO_2e/y) [3c]	85.9 ±39.1 (6.9%)	123.5 n.a. (11.5%)	2.7 ±1.2 (7.5%)	--	2.5 -1.2/+1.2 (--)	--		--	--	**2.5** **-1.2/+1.2** **(11.3%)**
Use, other C-containing (CO_2) (Mt CO_2e/y) [3d]			Incl. in prev.?		0.3 Unknown (--)					**0.3** **(1.4%)**
Production (CO_2) (some incl. N_2O) (Mt CO_2e/y) [3e]	438.5 ±37.1 (35.2%)	305.6[†] n.a. (28.5%)	8.5 ±0.8 (23.7%)	9.6 Mt n.a. (n.a.)	--	4.5 CO_2 only; Cdn prod'n		--	--	**7.5**** **(33.8%)**
Transport (mostly CO_2) (Mt CO_2e/y) [3g]	29.8 ±4.0 (2.5%)	37.2 n.a. (3.5%)	0.7 ±0.2 (1.9%)	--	--	--		--	--	**0.2** **(0.9%)**
Natural gas supply (CO_2 & CH_4) (Mt CO_2e/y) [3f]	--	--	--	--	--	--		--	--	**0.9**[§] **(4.1%)**
Total emissions (CO_2e) (Mt CO_2e/y)	1,244.9 ±185.6 (100%)	1070.9 n.a. (100%)	36.0 ±54.7 (100%)	--	--	--		--	--	**22.2** **(100%)**
Total N fertilizer quantity (Mt actual N/y)	107.7	126.9	2.8	2.5	--	--		--	--	**2.9**
Derived emissions coefficient, total emis'ns (tonnes CO_2e/tonne N)	11.56	8.63	12.85	--	--	--		--	--	**7.66**
Derived emissions coefficient, <u>production</u> only (tonnes CO_2e/tonne N)	4.07	2.41	3.04	3.93 (4.05 in prev. years)	--	--	3.180 (assumed to incl. urea CO_2)	2.19 Urea 4.44 UAN	3.04 NH_3 2.20 Urea 4.43 UAN 6.81 AN	**2.6 in 2020**[††] **3.7 in 1990**

Percentages in parentheses indicate percent of column total, i.e., percent of total fertilizer-related emissions. Uncertainty ranges are listed below tonnages—see "±" symbols. Green shading indicates sources; blue indicates comparables.

* ECCC NIR lists 11 Mt/y for this category. 8.5 Mt/y nets out the negative values reported under NIR category "Conservation tillage." See NIR Part 1, Table 5-1 and Section 5.4.1.7. See descripton of category 3a, above.

[†] IFA lists 389 Mt CO_2e for all fertilizer production: N, P, and K. This table takes 80% of the IFA value.

[‡] Production plant CO_2 only, i.e., excluding CO_2 from in-field lysis of urea.

[§] See text, above.

** Calculated using coefficient listed at bottom. See text re methodology.

[††] Weighted average derived fr. Brentrup emissions factors times percentages of each form of fert. used in Canada.

In addition to Table 5 citations, see S. Wood and A. Cowie, "A Review of Greenhouse Gas Emission Factors for Fertiliser Production," IEA - Task 38 (IEA, 2004); and esp. E. Walling and C. Vaneeckhaute, "Greenhouse Gas Emissions from Inorganic and Organic Fertilizer Production and Use: A Review of Emission Factors...," *Journal of Environmental Management* 276 (2020). See also Yara Internatinal, "It's Crops I Want, Not CO_2," https://www.yara.is/wp-content/uploads/2016/02/CO2-enska.pdf;

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79 Menegat, Ledo, and Tirado, "Greenhouse Gas Emissions from Global Production and Use of Nitrogen Synthetic Fertilisers...."

80 International Fertilizer Industry Association, "Fertilizers, Climate Change and Enhancing Agricultural Productivity....," 10.

81 2014 values provided by J. Dyer upon request. See also Dyer et al., "Integration of Farm Fossil Fuel Use with Local Scale Assessments of Biofuel Feedstock Production in Canada," in *Efficiency and Sustainability in Biofuel Production* (New York: Apple Academic Press, 2015); Dyer et al., "The Fossil Energy Use and CO_2 Emissions Budget for Canadian Agriculture," in *Sustainable Energy Solutions in Agriculture* (Boca Raton: CRC Press, 2014); and Dyer and Desjardins, "Carbon Dioxide Emissions Associated with the Manufacture of Tractors and Farm Machinery in Canada," *Biosystems Engineering* 93, no. 1.

82 "NIR 2022 Part 1."

83 Natural Resources Canada & Canadian Fertilizer Institute, "Canadian Ammonia Producers: Benchmarking Energy Efficiency," 13.

84 Cheminfo Services Inc., "Carbon Footprints for Canadian Crops: Canadian Fertilizer Production Data," Prepared for the Canadian Roundtable for Sustainable Crops (Markham, ON: CRSC, 2020).

85 Hoxha and Christensen, *The Carbon Footprint of Fertiliser Production*.

86 Brentrup et al., "Updated Carbon Footprint Values for Mineral Fertilizer from Different World Regions."

Omitted from our total of nitrogen-fertilizer-related emissions is N_2O from crop residue decomposition (see categories 5c and 5d). It is probably legitimate to assign to nitrogen fertilizer a large portion of the millions of tonnes recorded in those categories because that fertilizer is the original source of the N in the N_2O released via that crop residue decomposition. Or, seen another way, that decomposition represents *delayed* release of fertilizer-derived N_2O. If ECCC data can be disaggregated, and if one were to decide to assign an appropriate tonnage of emissions from decomposition, it is likely that total emissions from nitrogen fertilizer production and use could top 25 Mt CO_2e per year. Once emissions for fertilizer transport, upstream natural gas production, and methane releases at fertilizer production facilities are refined, that total could move higher still—perhaps nearing a third of total agricultural emissions.

Finally, regarding nitrogen fertilizer, ponder this: A large portion of the N_2O emissions from *manure* could be considered as downstream outputs from nitrogen fertilizer inputs. Synthetic nitrogen fertilizer is the primary source of reactive nitrogen inputs into Canadian agroecosystems—the underlying source of most of the N in N_2O, including much from manure. Imagine a hog, chicken, or cow eating grain or commercial rations grown using large inputs of synthetic nitrogen. Later, that animal's manure emits N_2O. Where did the N in that N_2O come from? Much came from fertilizer factories. The inflow of millions of tonnes of synthetic reactive N into our agricultural systems causes the outflow of N_2O by *many* channels, including via manure. The NFU is not advocating that a portion of manure N_2O be counted as emissions from nitrogen fertilizer, but it is illuminating to reflect on the large and diverse emissions footprint of that fertilizer. It is also illuminating to ponder the interconnected *systems* nature of agriculture and how key compounds such as reactive N and N_2O move through the system via diverse and interbraided pathways.

4a. Input manufacture, phosphorus (P) fertilizer

Mostly carbon dioxide; 2.6 Mt CO_2e/y in 2020 (uncertainty range moderate); 3.1% of Cdn. ag. emissions

This category estimates emissions from mining, processing, and transporting phosphorus fertilizer. We first located an emissions coefficient that could equate GHG emissions to fertilizer use: tonnes CO_2e / tonne P in fertilizer. Based on a brief literature search, in this Second Edition we adopted a coefficient from Cheminfo from a 2016/2020 report that looked specifically at Canadian production facilities: 2.130 tonnes CO_2e / tonne P_2O_5.[87] This value is higher than some others. For example, Walling and Vaneeckhaute[88] summarize a range of values and might suggest an emissions coefficient of 1.1 tonnes CO_2e / tonne P_2O_5. Cheminfo notes that "Canada's cradle to production facility gate lifecycle GHG emissions intensity for phosphate fertilizers is significantly higher even than the global average and the average of all other regions for cradle to use lifecycle.... Contributing to Canada's relatively high GHG intensity level for phosphate fertilizers are emissions associated with Moroccan mining and the long freight distance travelled to bring the phosphate rock raw material to Redwater, AB." Cheminfo's report includes a table detailing travel distances by various transport modes and tonne-mile emissions for each.

Sources: Methodology and calculations by NFU based on published sources. See text above and footnote below. Phosphorus fertilizer tonnage is from Stats Can Tables 32-10-0039-01 and 32-10-0274-01.

4b. Input manufacture, potassium (K) fertilizer

Mostly carbon dioxide; 0.3 Mt CO_2e/y in 2020 (uncertainty range high); 0.4% of Cdn. ag. emissions

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[87] Cheminfo Services Inc., "Carbon Footprints for Canadian Crops: Canadian Fertilizer Production Data."

[88] Eric Walling and Céline Vaneeckhaute, "Greenhouse Gas Emissions from Inorganic and Organic Fertilizer Production and Use: A Review of Emission Factors and Their Variability," *Journal of Environmental Management* 276 (December 2020): 111211, https://doi.org/10.1016/j.jenvman.2020.111211.

This category estimates emissions from potassium fertilizer (potash) mining and processing. Methodology is similar to that used for estimating emissions from phosphorus production. We used an emissions coefficient from Brentrup[89]: 0.416 tonnes CO_2e / tonne K_2O. Transport emissions are omitted, though these will be small.

Sources: Methodology and calculation by NFU. See text above and footnote below.

Note that Cheminfo/Canadian Round Table for Sustainable Crops[90] provide an emission coefficient that is lower: 0.334 tonnes CO_2e / tonne K_2O. Future Editions of this report may want to consider using that lower coefficient. Due to the relatively small tonnage of emissions in this category, however, the effect will be negligible in relation to total Canadian agricultural emissions.

4c. Input manufacture, machinery

Carbon dioxide; 2.6 Mt CO_2e/y in 2020 (uncertainty range unknown); 3.1% of Cdn. ag. emissions

This category estimates the emissions from the production of the farm machinery used on Canadian farms, including production of steel, rubber, glass, etc.

Future editions of this report may need updated data as decarbonization of electrical grids reduce emissions from steelmaking and manufacturing.

Sources: Data for the years 1991, 1996, 2001, 2006, 2011, and 2014 provided on request by James Dyer. See also category 8b, below. See also Dyer and Desjardins, "Carbon Dioxide Emissions Associated with the Manufacturing of Tractors and Farm Machinery in Canada," *Biosystems Engineering* 93, no. 1 (Jan. 2006).

5a. Soils, organic nitrogen fertilizer, direct

Nitrous oxide; 1.5 Mt CO_2e/y in 2020 (uncertainty range 1.0–2.2 Mt); 1.8% of Cdn. ag. emissions

As with synthetic nitrogen fertilizer, the addition of organic sources of N increases emissions of N_2O. This emissions category includes manure from drylot, liquid, and other manure management systems, as well as human biosolids from wastewater treatment plants (the latter being only a small portion).

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.4.1.2 and Table 5-7.

5b. Soils, organic nitrogen fertilizer, indirect

Nitrous oxide; 0.7 Mt CO_2e/y in 2020 (uncertainty range approx. −75% to +100%); 0.8% of Cdn. ag. emissions

This category captures off-site N_2O emissions resulting from volatilization, runoff, and leaching of nitrogen compounds. For more explanation, see category 3b, "Soils, synthetic nitrogen fertilizer, indirect," above.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 contains values for "Agricultural soils, indirect sources." Upon request, ECCC subdivided this data into subcategories: inorganic nitrogen fertilizers; organic nitrogen fertilizers; crop residue decomposition; and manure on pasture, range, and paddock.

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[89] Brentrup et al., "Updated Carbon Footprint Values for Mineral Fertilizer from Different World Regions."

[90] Cheminfo Services Inc., "Carbon Footprints for Canadian Crops: Canadian Fertilizer Production Data," Table 2.

5c. Soils, crop residue decomposition, direct

Nitrous oxide; 4.5 Mt CO_2e/y in 2020 (uncertainty range 2.9–6.5 Mt); 5.4% of Cdn. ag. emissions

After most crops are harvested, the bulk of the plant mass is left in the field to decompose. That biomass is a source of nitrogen and, thus, of N_2O. Emissions from this category are large: 5 percent of total agricultural emissions. Though in this report we do not assign a portion of these emissions to synthetic nitrogen fertilizer, doing so should be considered, as synthetic nitrogen fertilizer is the original source of much of the reactive N in these N_2O emissions. Currently, however, it appears that data is lacking to segment these crop residue N_2O emissions by nitrogen sources (e.g., organic fertilizer, natural fixation, and synthetic fertilizer). If possible, ECCC should segment N_2O from residue decomposition according to N source.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.4.1.3 and Table 5-7.

Note: There is large uncertainty and variability around these values as decomposition emissions are a function of crop type, yield, harvest date, post-harvest weather, presence or absence of cover crops, etc.

5d. Soils, crop residue decomposition, indirect

Nitrous oxide; 0.9 Mt CO_2e/y in 2020 (uncertainty range unknown); 1.1% of Cdn. ag. emissions

Volatilization, runoff, and leaching of nitrogen compounds causes subsequent, off-site N_2O emissions. For an explanation, see category 3b, "Soils, synthetic nitrogen fertilizer, indirect," above.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 contains values for "Agricultural soils, indirect sources." Upon request, ECCC subdivided this data into subcategories: inorganic nitrogen fertilizers; organic nitrogen fertilizers; crop residue decomposition; and manure on pasture, range, and paddock.

5e. Soils, mineralization of soil organic carbon, direct

Nitrous oxide; 0.8 Mt CO_2e/y in 2020 (uncertainty range 0.5–1.2 Mt); 1.0% of Cdn. ag. emissions

This category measures N_2O, not CO_2, from soils due to changes in land use and tillage. ECCC explains: "Carbon loss in soils as a result of changes to land management practices is accounted for within the Cropland category of the LULUCF sector.... Nonetheless, nitrogen mineralization associated with the loss of soil organic carbon contributes to the overall N balance of agricultural lands. This nitrogen, once in an inorganic form, is prone to loss in the form of N_2O.... Emissions are estimated ... based on the amount of nitrogen contained in soil organic matter that is lost as a result of changes in cropland management practices multiplied by the emission factor...." This measure is trending upward.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.4.1.5 and Table 5-7.

5f. Soils, adjustment for summerfallow, direct

Nitrous oxide; discontinued in *NIR 2022*.

Up to and including *NIR 2021*, this was a measure of N_2O from summerfallow. ECCC explains that "The reporting of summerfallow emissions as a country-specific methodology, was discontinued in this submission to avoid double counting following the introduction of a methodology for estimating soil organic carbon from changes in crop productivity."[91] For the latter, see category 1f.

5g. Soils, adjustment for irrigation, direct

Nitrous oxide; 1.3 Mt CO_2e/y in 2020 (uncertainty range approx ±50%); 1.6% of Cdn. ag. emissions

ECCC explains: "Higher soil water content under irrigation increases the potential for N_2O emissions through increased biological activity, reducing soil aeration ... and thus enhancing denitrification.."[92] Recent research suggests that actual effects of irrigation on emissions may be lower that ECCC reports.[93]

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.4.1.8.

5h. Soils, manure on pasture etc., direct

Nitrous oxide; 0.2 Mt CO_2e/y in 2020 (uncertainty range approx. ±65%); 0.2% of Cdn. ag. emissions

Emissions in this category are small and declining as cattle numbers decline. In preparing future editions of this report, the authors and reviewers should consider whether a portion of this category and the "organic nitrogen fertilizer" categories (5a and 5b) should be grouped with cattle emissions.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.4.1.4 and Table 5-7.

6a. Burning crop residues

Methane and nitrous oxide; 0.05 Mt CO_2e/y in 2020 (uncertainty range approx. ±65%); <0.1% of emissions

Emissions of carbon dioxide are not included in this category, as CO_2 is assumed to move in a circle from the atmosphere to the crop (during photosynthesis and growth) then back to the atmosphere (during burning); hence, no new CO_2 is added to the atmosphere when crops are burnt (unlike when fossil fuels are burnt). Emissions in this category are now disappearingly small, but higher in the past: 0.2 Mt in 1990.

Sources: ECCC, *NIR 2022*, Part 1, Table 5-1 (with data for years omitted from the Table provided by ECCC). See *NIR 2022*, Part 1, section 5.5.1.

7a. Lime application

Carbon dioxide; 0.2 Mt CO_2e /y in 2020 (uncertainty range ±0.14 Mt); 0.2% of Cdn. ag. emissions

Limestone ($CaCO_3$) is added to soils to neutralize acidic soils and thereby make nutrients more available and provide other benefits. CO_2 is released from subsequent bicarbonate reactions. The trendline is downward.

Sources: ECCC, "Canada. 2022 Common Reporting Format (CRF) Table," UNFCCC Documents, accessed May 15, 2022, https://unfccc.int/documents/461923 Table 10s1. See NIR Part 1, section 5.6.

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[91] "NIR 2022 Part 1," 163.

[92] "NIR 2022 Part 1," 163.

[93] Cody David et al., "Current Inventory Approach Overestimates the Effect of Irrigated Crop Management on Soil-Derived Greenhouse Gas Emissions in the Semi-Arid Canadian Prairies," *Agricultural Water Management* 208 (September 30, 2018).

8a. Fuel use, diesel, off-road

Mostly carbon dioxide; 10.3 Mt CO_2e/y in 2020 (uncertainty range ±1.4%); 12.4% of Cdn. ag. emissions

This category slightly underestimates total emissions from agricultural diesel fuel use because it omits (some) on-road combustion in light-, medium-, and heavy-duty trucks. This omission is minor, especially because this report draws its boundary at the farmgate and therefore omits post-farm farm product transport emissions (also, much of that fuel use is in commercial, not farmers', trucks).

Note: In calculating emissions from nitrogen fertilizer, this report includes a category for the emissions from upstream natural gas production and processing. Arguably, the same could be done here: adding categories for emissions from upstream oil extraction and refining. For on-farm diesel, for example, adding upstream emissions would add 20 to 30 percent,[94] or 2 to 3 Mt. This methodological improvement can be considered for future editions of this report.

Sources: Disaggregation of NIR data provided, upon request, by ECCC. For underlying aggregated data, see ECCC, Table A10-2: GHG Emissions for Canada by Canadian Economic Sector, 1990-2020, https://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/B-Economic-Sector/?lang=en

8b. Fuel use, gasoline, on- and off-road

Mostly carbon dioxide; 0.7 Mt CO_2e/y in 2020 (uncertainty range unknown); 0.8% of Cdn. ag. emissions

This category reflects emissions from farmers' use of gasoline on- and off-road. The trendline is a slow rise.

Future editions may want to access newer data, as emissions since 2014 are extrapolations.

Sources: Data for 1991, 1996, 2001, 2006, 2011, and 2014 provided on request by J. Dyer. Interpolation and extrapolation by NFU. This data has its basis in several publications, incl.: J. Dyer et al., "Integration of Farm Fossil Fuel Use with Local Scale Assessments of Biofuel Feedstock Production in Canada," in *Efficiency and Sustainability in Biofuel Production*, Ed. Barnabas Gikonyo (New York: Apple Academic Press, 2015); J. Dyer et al., "The Fossil Energy Use and CO_2 Emissions Budget for Canadian Agriculture," in *Sustainable Energy Solutions in Agriculture* (Boca Raton: CRC Press, 2014); and J. Dyer and R. Desjardins, "Carbon Dioxide Emissions Associated with the Manufacturing of Tractors and Farm Machinery in Canada," *Biosystems Engineering* 93, no. 1 (Jan. 2006). ECCC data is not used as it covers only off-road use.

8c. Fuel use, fuel oil, light and heavy, stationary

Mostly carbon dioxide; 0.2 Mt CO_2e/y in 2020 (uncertainty range unknown); 0.2% of Cdn. ag. emissions

This is light fuel oil and heavy fuel oil used for heating and other stationary uses on farms. Recalculations in *NIR 2022* significantly reduced emissions in this category.

Sources: Disaggregation of NIR data provided upon request. For underlying aggregated data, see ECCC, Table A10-2: GHG Emissions for Canada by Canadian Economic Sector, 1990-2020, https://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/B-Economic-Sector/?lang=en

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[94] Adam R Brandt, "Upstream Greenhouse Gas (GHG) Emissions from Canadian Oil Sands as a Feedstock for European Refineries," n.d., 4.

8d. Fuel use, natural gas and propane, stationary

Mostly carbon dioxide; 2.7 Mt CO_2e/y in 2020 (uncertainty range unknown); 3.3% of Cdn. ag. emissions

This is natural gas and propane used for heating farm buildings and water, drying grain, and other on-farm stationary uses. The trendline is upward but with large weather-related year-to-year fluctuations.

Sources: Disaggregation of NIR data provided upon request. For underlying aggregated data, see ECCC, Table A10-2: GHG Emissions for Canada by Canadian Economic Sector, 1990-2020, https://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/B-Economic-Sector/?lang=en

8e. Fuel use, electricity supply

Mostly carbon dioxide; 0.3 Mt CO_2e/y in 2020 (uncertainty range high); 0.3% of Cdn. ag. emissions

Farms use significant amounts of electricity for lighting, heating and cooling, running electric motors in certain equipment, and pumping, including irrigation. This category represents the emissions from electricity generating stations that burn coal or natural gas. Emissions in this category are declining and will continue to do so as coal-fired stations are retired and more electricity comes from low-emissions sources. Future editions of this report should attempt to access newer data, as values after 2014 are linear extrapolations.

Sources: Data for the years 1991, 1996, 2001, 2006, 2011, and 2014 provided on request by James Dyer. See category 8b, "Fuel use, gasoline, on- and off-road," above.

Concluding remarks

We can be certain of the following: Canadian agricultural emissions are high and rising; the main driver for the increase is rising rates of synthetic nitrogen fertilizer use; the largest single contributor to agricultural GHG emissions is beef production; and fossil fuel use is a larger factor than is often acknowledged.

What is less certain are the exact emissions in most of the categories detailed above. There are significant uncertainties for many of the categories reported by ECCC and sometimes even more so for those not reported and instead calculated by academics or by the NFU based on reports by academics. Much work needs to be done to reduce the uncertainties. This is especially true as we endeavour to measure and report emissions reductions from on-farm changes—reductions that will initially be small though very important to quantify and document.

Nonetheless, we have more than enough data and more than enough precision to move forward swiftly, energetically, and courageously to reduce agricultural emissions. Commitments by governments to cut emissions from methane, from fertilizer, and from the economy as a whole provide clear signals that we need to act now and in each coming year to reduce emissions from all agricultural categories. The NFU hopes that this report and its data will help policymakers and farmers in this important work and, most importantly, inform the creation of sound, effective government policies and programs that can support and assist farmers as they make the needed changes to move to lower-emissions systems.

Key reports and information sources

For those interested in GHG emissions, key documents from the Government of Canada include:

- Environment and Climate Change Canada (ECCC), GHG emission data tables, https://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/

- ECCC, *National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada*, https://unfccc.int/documents/461919 This three-part annual report is the primary source for almost all emissions values. See especially:
    - Part 1, section 2.3.3, Agriculture Sector
    - Part 1, Ch. 5, Agriculture
    - Part 1, Table 5–1, Short-and Long-Term Changes in Emissions from the Agriculture Sector
    - Part 1, Chapter 6, Land Use, Land Use Change, and Forestry

- 2022 Common Reporting Format (CRF) Table, Canada, https://unfccc.int/documents/461923

- ECCC, Canada's Biennial Report on Climate Change, https://unfccc.int/documents/209928

- ECCC, Canada's Greenhouse Gas and Air Pollutant Emissions Projections 2020, https://publications.gc.ca/collections/collection_2021/eccc/En1-78-2020-eng.pdf

- ECCC, "A Healthy Environment and a Healthy Economy: Canada's Strengthened Climate Plan to Create Jobs and Support People, Communities and the Planet" (Ottawa: ECCC, December 2020), https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/healthy_environment_healthy_economy_plan.pdf

Appendix A: Summary of changes between the First Edition (Mar. 2022) and Second (June 2022)

As noted, *NIR 2022* makes very significant changes to methodologies for calculating several categories of emissions and fluxes. For those who wish to compare, visually, the emissions and fluxes reported in *NIR 2021* with those reported in *NIR 2022*, please compare Figure 3, above, with Figure 6, below.

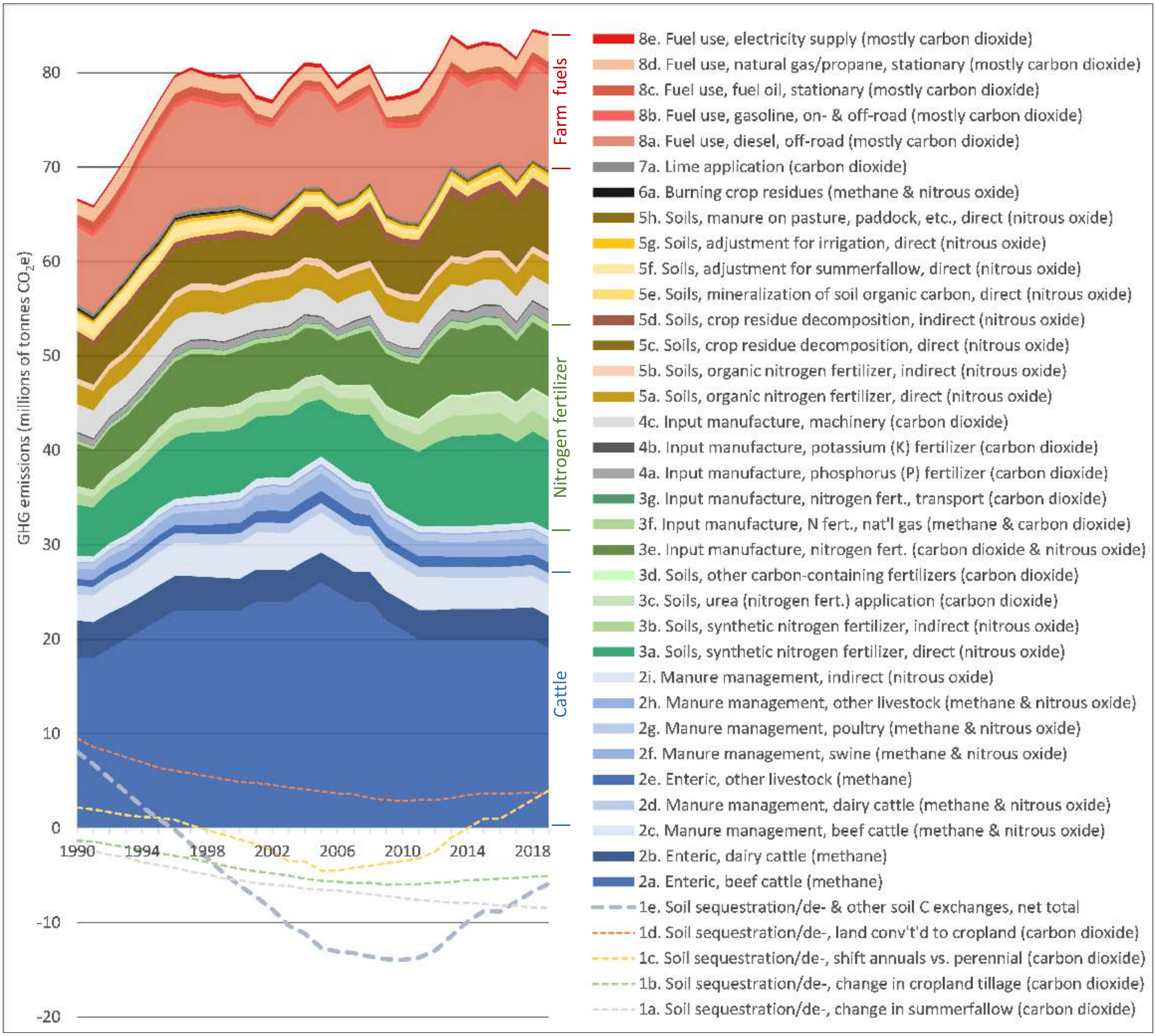

Figure 6. Comprehensive, detailed picture of Canadian agricultural emissions, 1990–2019, based on *NIR 2021* methodology and data (from the First Edition of this report).

Sources: ECCC, *National Inventory Report 1990–2019*, Part 1, Tables 5-1, 6-1, and 6-9 (with data for years omitted from the Tables provided by ECCC); Additional data and sub-categorizations of published data provided by ECCC upon request; ECCC, Common Reporting Format (CRF) Tables; Data from Dyer et al.; other sources; and NFU own calculations. The vast majority of categories are based on ECCC data. For complete and detailed sources and notes for each category, see Part 4, above.

1. 2022 *National Inventory Report* data: Emissions

In April 2022, ECCC released its annual *National Inventory Report* (*NIR*). *NIR 2022* data includes 2020 emissions values. Those values were added to this Edition, extending the time series to 2020. Also, *NIR 2022* included revised values for several categories of emissions, most notably emissions from fertilizer use. The two partial tables below are excerpted from *NIR 2022* and give an overview of changes between *NIR 2021* and *2022*. Notice the magnitude of the revisions: 10 percent to 30+ percent.

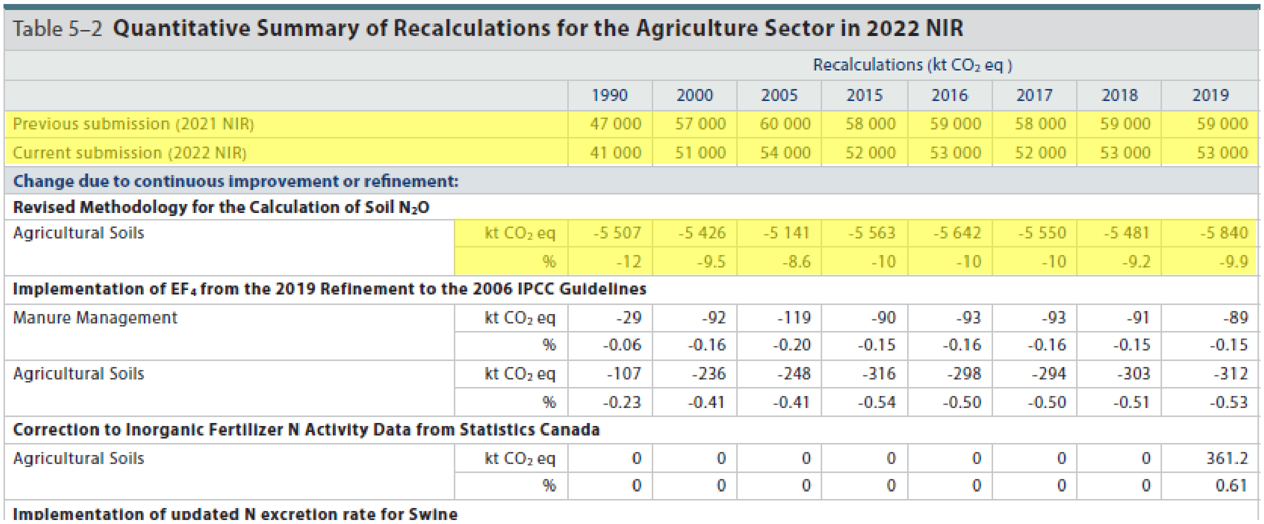

Table 5–2 **Quantitative Summary of Recalculations for the Agriculture Sector in 2022 NIR**

		Recalculations (kt CO_2 eq)							
		1990	2000	2005	2015	2016	2017	2018	2019
Previous submission (2021 NIR)		47 000	57 000	60 000	58 000	59 000	58 000	59 000	59 000
Current submission (2022 NIR)		41 000	51 000	54 000	52 000	53 000	52 000	53 000	53 000
Change due to continuous improvement or refinement:									
Revised Methodology for the Calculation of Soil N_2O									
Agricultural Soils	kt CO_2 eq	-5 507	-5 426	-5 141	-5 563	-5 642	-5 550	-5 481	-5 840
	%	-12	-9.5	-8.6	-10	-10	-10	-9.2	-9.9
Implementation of EF_4 from the 2019 Refinement to the 2006 IPCC Guidelines									
Manure Management	kt CO_2 eq	-29	-92	-119	-90	-93	-93	-91	-89
	%	-0.06	-0.16	-0.20	-0.15	-0.16	-0.16	-0.15	-0.15
Agricultural Soils	kt CO_2 eq	-107	-236	-248	-316	-298	-294	-303	-312
	%	-0.23	-0.41	-0.41	-0.54	-0.50	-0.50	-0.51	-0.53
Correction to Inorganic Fertilizer N Activity Data from Statistics Canada									
Agricultural Soils	kt CO_2 eq	0	0	0	0	0	0	0	361.2
	%	0	0	0	0	0	0	0	0.61
Implementation of updated N excretion rate for Swine									

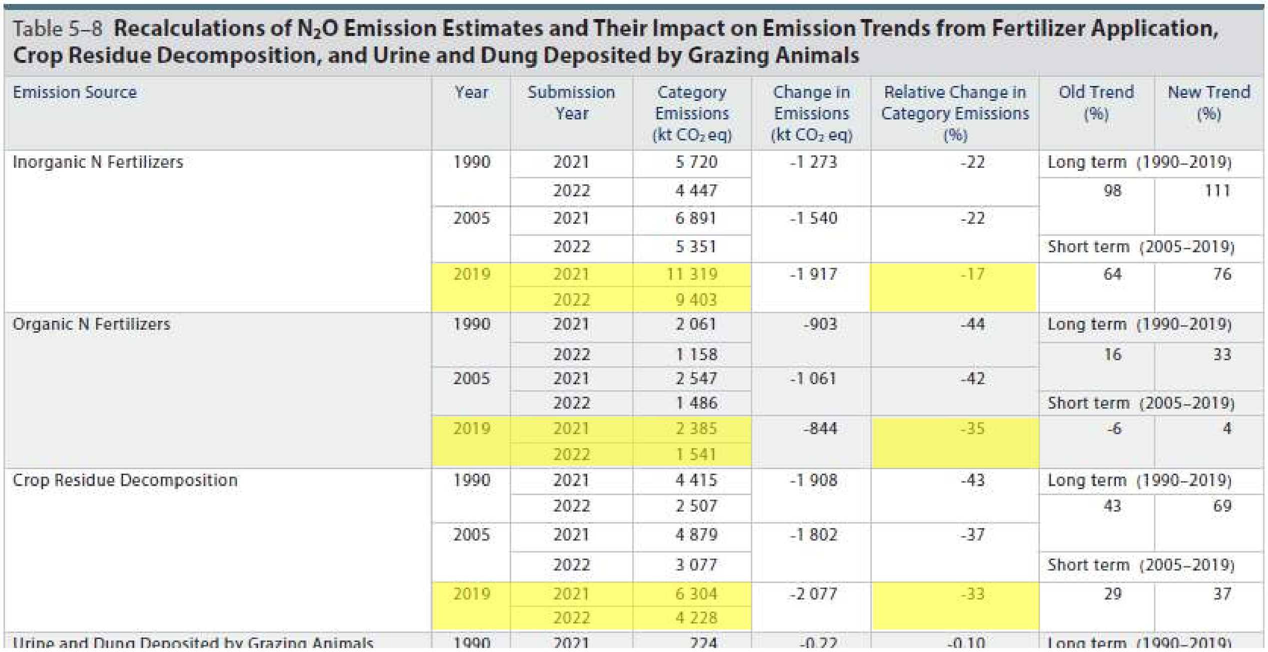

Table 5–8 **Recalculations of N_2O Emission Estimates and Their Impact on Emission Trends from Fertilizer Application, Crop Residue Decomposition, and Urine and Dung Deposited by Grazing Animals**

Emission Source	Year	Submission Year	Category Emissions (kt CO_2 eq)	Change in Emissions (kt CO_2 eq)	Relative Change in Category Emissions (%)	Old Trend (%)	New Trend (%)
Inorganic N Fertilizers	1990	2021	5 720	-1 273	-22	Long term (1990–2019)	
		2022	4 447			98	111
	2005	2021	6 891	-1 540	-22		
		2022	5 351			Short term (2005–2019)	
	2019	2021	11 319	-1 917	-17	64	76
		2022	9 403				
Organic N Fertilizers	1990	2021	2 061	-903	-44	Long term (1990–2019)	
		2022	1 158			16	33
	2005	2021	2 547	-1 061	-42		
		2022	1 486			Short term (2005–2019)	
	2019	2021	2 385	-844	-35	-6	4
		2022	1 541				
Crop Residue Decomposition	1990	2021	4 415	-1 908	-43	Long term (1990–2019)	
		2022	2 507			43	69
	2005	2021	4 879	-1 802	-37		
		2022	3 077			Short term (2005–2019)	
	2019	2021	6 304	-2 077	-33	29	37
		2022	4 228				
Urine and Dung Deposited by Grazing Animals	1990	2021	224	-0.22	-0.10	Long term (1990–2019)	

***NIR 2022* Tables 5–2 and 5–8.**

In this Second Edition, all emissions values from *NIR 2021* were replaced with those from *NIR 2022*.

2. 2022 *National Inventory Report* data: Soil carbon fluxes

In addition to very significant changes in methodology and values for emissions, even larger changes were made to methodologies and values surrounding soil carbon fluxes—soil carbon sequestration and desequestration. ECCC says that "This year's [NIR] submission includes significant recalculations in reported estimates for Forest Land, Cropland and Harvested Wood Products categories. The most notable recalculations were due to (i) updated methods to estimate changes in soil organic carbon (SOC) impacted by crop productivity changes and manure application...."[95]

The two tables below highlight the magnitude of the changes. Note, for example, 2019, when the removals/sequestration (negative values) for cropland more than doubled, from −7.8 Mt to −17 Mt.

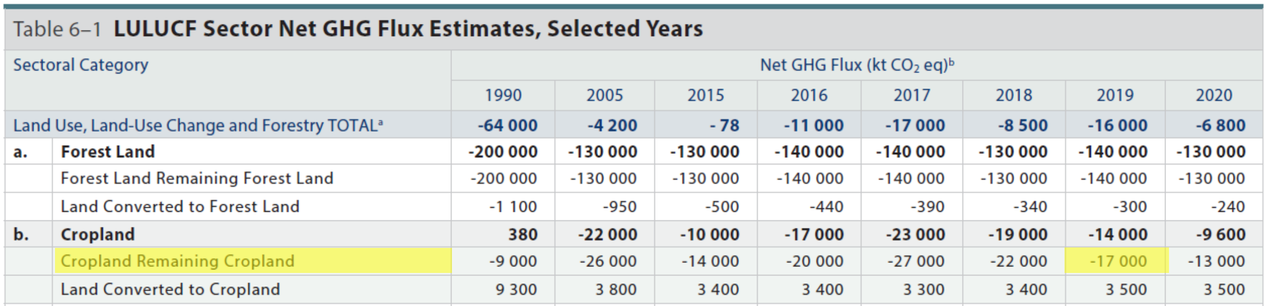

Table 6–1 **LULUCF Sector Net GHG Flux Estimates, Selected Years**

Sectoral Category		Net GHG Flux (kt CO_2 eq)[b]							
		1990	2005	2015	2016	2017	2018	2019	2020
Land Use, Land-Use Change and Forestry TOTAL[a]		**-64 000**	**-4 200**	**- 78**	**-11 000**	**-17 000**	**-8 500**	**-16 000**	**-6 800**
a.	**Forest Land**	**-200 000**	**-130 000**	**-130 000**	**-140 000**	**-140 000**	**-130 000**	**-140 000**	**-130 000**
	Forest Land Remaining Forest Land	-200 000	-130 000	-130 000	-140 000	-140 000	-130 000	-140 000	-130 000
	Land Converted to Forest Land	-1 100	-950	-500	-440	-390	-340	-300	-240
b.	**Cropland**	**380**	**-22 000**	**-10 000**	**-17 000**	**-23 000**	**-19 000**	**-14 000**	**-9 600**
	Cropland Remaining Cropland	-9 000	-26 000	-14 000	-20 000	-27 000	-22 000	-17 000	-13 000
	Land Converted to Cropland	9 300	3 800	3 400	3 400	3 300	3 400	3 500	3 500

NIR 2022 **Table 6–1**

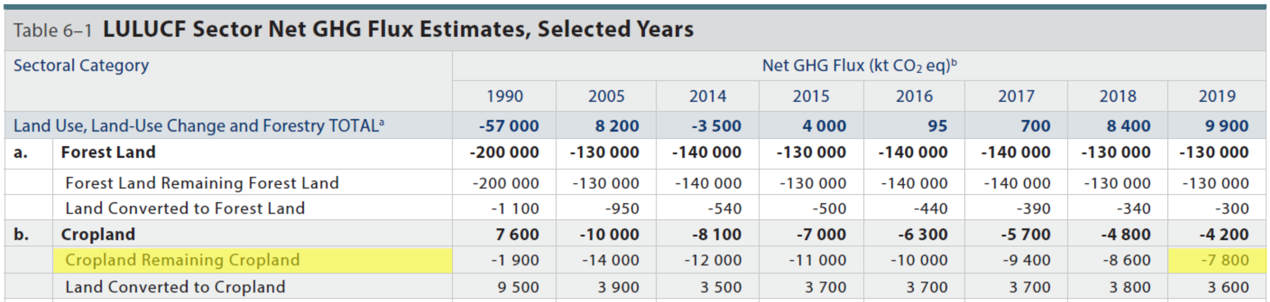

Table 6–1 **LULUCF Sector Net GHG Flux Estimates, Selected Years**

Sectoral Category		Net GHG Flux (kt CO_2 eq)[b]							
		1990	2005	2014	2015	2016	2017	2018	2019
Land Use, Land-Use Change and Forestry TOTAL[a]		**-57 000**	**8 200**	**-3 500**	**4 000**	**95**	**700**	**8 400**	**9 900**
a.	**Forest Land**	**-200 000**	**-130 000**	**-140 000**	**-130 000**	**-140 000**	**-140 000**	**-130 000**	**-130 000**
	Forest Land Remaining Forest Land	-200 000	-130 000	-140 000	-130 000	-140 000	-140 000	-130 000	-130 000
	Land Converted to Forest Land	-1 100	-950	-540	-500	-440	-390	-340	-300
b.	**Cropland**	**7 600**	**-10 000**	**-8 100**	**-7 000**	**-6 300**	**-5 700**	**-4 800**	**-4 200**
	Cropland Remaining Cropland	-1 900	-14 000	-12 000	-11 000	-10 000	-9 400	-8 600	-7 800
	Land Converted to Cropland	9 500	3 900	3 500	3 700	3 700	3 700	3 800	3 600

NIR 2021 **Table 6–1**

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[95] "NIR 2022 Part 1," 171.

Table 6–9 provides additional detail.

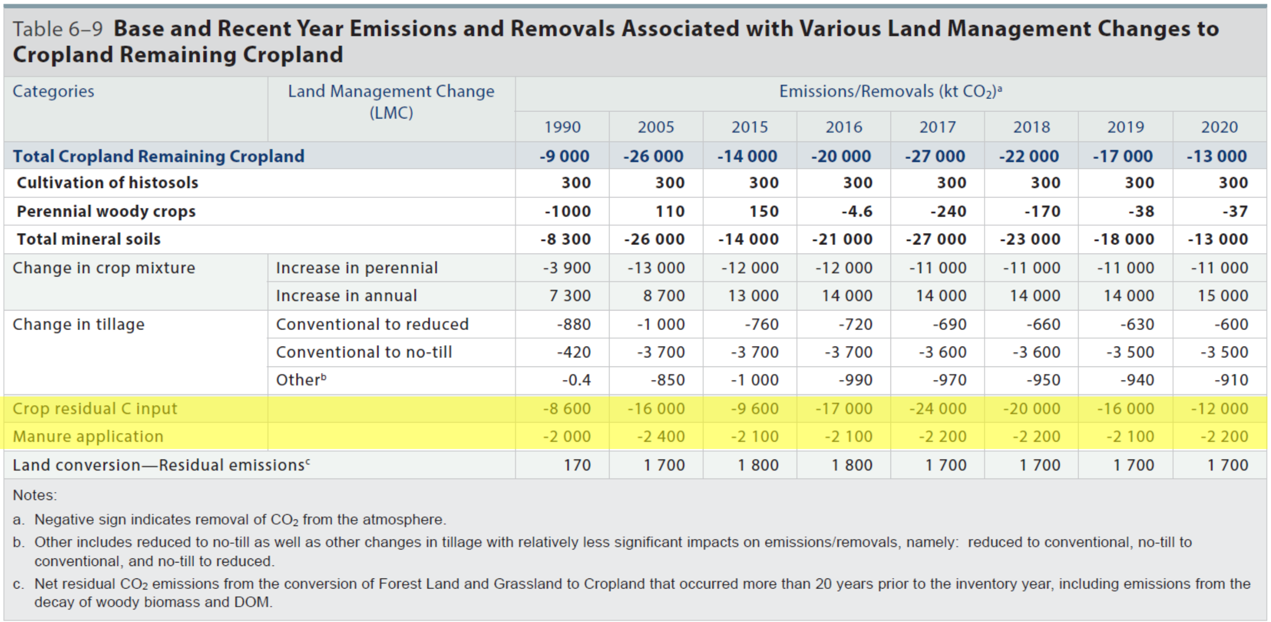

Table 6–9 **Base and Recent Year Emissions and Removals Associated with Various Land Management Changes to Cropland Remaining Cropland**

Categories	Land Management Change (LMC)	Emissions/Removals (kt CO_2)[a]							
		1990	2005	2015	2016	2017	2018	2019	2020
Total Cropland Remaining Cropland		**-9 000**	**-26 000**	**-14 000**	**-20 000**	**-27 000**	**-22 000**	**-17 000**	**-13 000**
Cultivation of histosols		**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**
Perennial woody crops		**-1000**	**110**	**150**	**-4.6**	**-240**	**-170**	**-38**	**-37**
Total mineral soils		**-8 300**	**-26 000**	**-14 000**	**-21 000**	**-27 000**	**-23 000**	**-18 000**	**-13 000**
Change in crop mixture	Increase in perennial	-3 900	-13 000	-12 000	-12 000	-11 000	-11 000	-11 000	-11 000
	Increase in annual	7 300	8 700	13 000	14 000	14 000	14 000	14 000	15 000
Change in tillage	Conventional to reduced	-880	-1 000	-760	-720	-690	-660	-630	-600
	Conventional to no-till	-420	-3 700	-3 700	-3 700	-3 600	-3 600	-3 500	-3 500
	Other[b]	-0.4	-850	-1 000	-990	-970	-950	-940	-910
Crop residual C input		-8 600	-16 000	-9 600	-17 000	-24 000	-20 000	-16 000	-12 000
Manure application		-2 000	-2 400	-2 100	-2 100	-2 200	-2 200	-2 100	-2 200
Land conversion—Residual emissions[c]		170	1 700	1 800	1 800	1 700	1 700	1 700	1 700

Notes:

a. Negative sign indicates removal of CO_2 from the atmosphere.

b. Other includes reduced to no-till as well as other changes in tillage with relatively less significant impacts on emissions/removals, namely: reduced to conventional, no-till to conventional, and no-till to reduced.

c. Net residual CO_2 emissions from the conversion of Forest Land and Grassland to Cropland that occurred more than 20 years prior to the inventory year, including emissions from the decay of woody biomass and DOM.

***NIR 2022* Table 6–9**

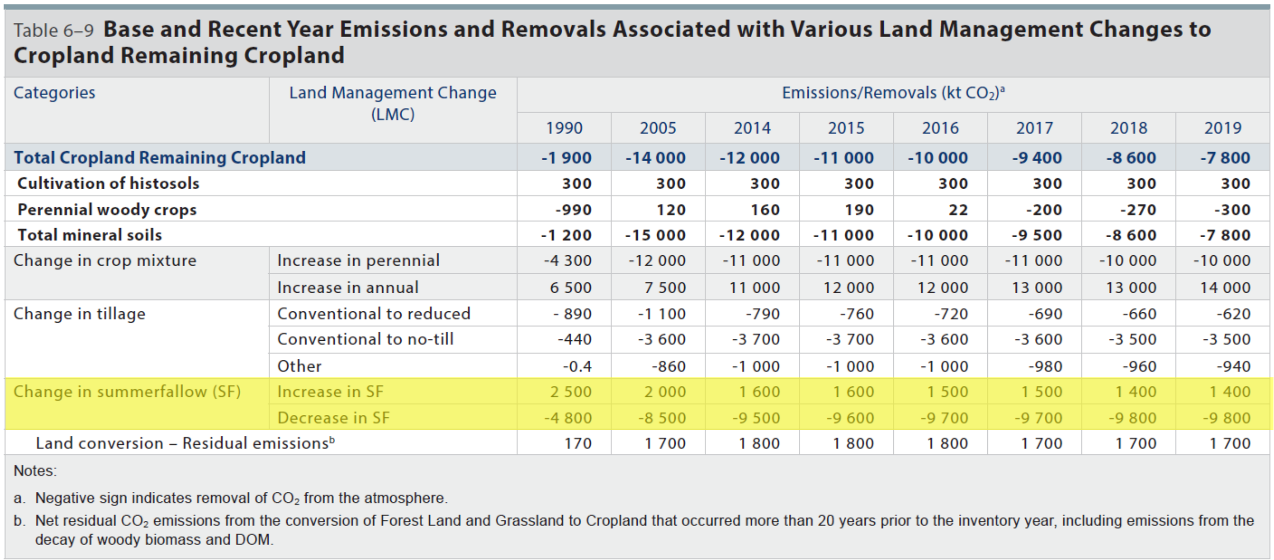

Table 6–9 **Base and Recent Year Emissions and Removals Associated with Various Land Management Changes to Cropland Remaining Cropland**

Categories	Land Management Change (LMC)	Emissions/Removals (kt CO_2)[a]							
		1990	2005	2014	2015	2016	2017	2018	2019
Total Cropland Remaining Cropland		**-1 900**	**-14 000**	**-12 000**	**-11 000**	**-10 000**	**-9 400**	**-8 600**	**-7 800**
Cultivation of histosols		**300**	**300**	**300**	**300**	**300**	**300**	**300**	**300**
Perennial woody crops		**-990**	**120**	**160**	**190**	**22**	**-200**	**-270**	**-300**
Total mineral soils		**-1 200**	**-15 000**	**-12 000**	**-11 000**	**-10 000**	**-9 500**	**-8 600**	**-7 800**
Change in crop mixture	Increase in perennial	-4 300	-12 000	-11 000	-11 000	-11 000	-11 000	-10 000	-10 000
	Increase in annual	6 500	7 500	11 000	12 000	12 000	13 000	13 000	14 000
Change in tillage	Conventional to reduced	- 890	-1 100	-790	-760	-720	-690	-660	-620
	Conventional to no-till	-440	-3 600	-3 700	-3 700	-3 600	-3 600	-3 500	-3 500
	Other	-0.4	-860	-1 000	-1 000	-1 000	-980	-960	-940
Change in summerfallow (SF)	Increase in SF	2 500	2 000	1 600	1 600	1 500	1 500	1 400	1 400
	Decrease in SF	-4 800	-8 500	-9 500	-9 600	-9 700	-9 700	-9 800	-9 800
Land conversion – Residual emissions[b]		170	1 700	1 800	1 800	1 800	1 700	1 700	1 700

Notes:

a. Negative sign indicates removal of CO_2 from the atmosphere.

b. Net residual CO_2 emissions from the conversion of Forest Land and Grassland to Cropland that occurred more than 20 years prior to the inventory year, including emissions from the decay of woody biomass and DOM.

***NIR 2021* Table 6–9**

Note, again, the differing methodologies and the large adjustments to the values. *NIR 2022* adds a category “Crop residual C input” and subsumes within that the category “Change in Summerfallow.” *NIR 2022* also adds “Manure application.” Again, changes are large: 10 to 20 Mt in many years.

ECCC explains its revisions:

> In this submission, significant recalculations occurred due to: i) the implementation of the IPCC Tier 2 Steady State approach for estimating the change in soil C storage as impacted by crop productivity/crop residue C input, ii) the change in soil C storage as influenced by manure application, iii) elimination of summerfallow as a separate LMC to avoid double counting of SOC change with changes in crop productivity, and iv) an update to land-use

> coverage, which impacted cropland land management area estimates throughout the inventory time series.
>
> The implementation of new methodologies for crop productivity and manure application increased net CO_2 removals to soil by 10 Mt for 1990, 18 Mt for 2005, and 18 Mt in 2020. The elimination of summerfallow as a separate LMC reduced soil CO_2 removals by 2.3 Mt in 1990, 6.5 Mt in 2005, and 8.4 Mt in 2020.
>
> A new version of land-use coverage that contains revised mapping of agricultural lands throughout all years of the time series was used to generate this year's inventory. This change impacted estimates of agricultural land management areas over all interpolated years. On a national scale, land mapped as cropland ranged from 0.5% (0.25 Mha) higher in 1990 to 0.9% (0.47 Mha) lower in 2020 than cropland estimates in 2021 NIR.
>
> The update in areas of tillage practices and perennial/annual crop mixture activity data resulted in an increase of soil CO_2 emissions of 1.3 Mt in 1990 and 0.25 Mt in 2005, and an increase of net CO_2 removals by soils of 0.1 Mt in 2020.
>
> The combined effect of these changes was *an increase in CO_2 removals by mineral soils of 7.1 Mt in 1990, 11 Mt in 2005, and 9.8 Mt in 2020* [italics added].[96]

As the Tables and italicized text in the quote make clear: revisions to soil carbon sequestration are large.

3. Soil carbon fluxes from changes in woody biomass on agricultural land

This Second Edition of this report adds a category 1a, changes in woody biomass. This data was previously reported by ECCC, but not included in the First Edition of this report.

4. Adjustment to emissions factor for production of phosphorus (P) fertilizer

To calculate emissions from the production of phosphorus fertilizer (category 4a), the First Edition of this report used an emissions factor of 1.1 tonnes CO_2e / tonne P_2O_5. This Second Editions uses an emissions factor of 2.130, based on a study of Canadian fertilizer production emissions from Cheminfo.[97] For additional details, see description of category 4a, above.

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[96] "NIR 2022 Part 1," 191.

[97] Cheminfo Services Inc., "Carbon Footprints for Canadian Crops: Canadian Fertilizer Production Data."