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PLANNING TO FAIL

A Case Study of Canada's Fertilizer Based Emission Reduction Target

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A Case Study of Canada's Fertilizer Based Emission Target.

Technical Report.
April 2023

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ABSTRACT

Target setting is an important step in the development of public policy. Targets provides a clear indication of the government's policy objectives and priorities. They also provide stakeholders clear policy direction, enabling them to plan, monitor, and deliver on policy objectives. To be effective targets need to be well-defined, measurable, and achievable. This report examines the Government of Canada’s fertilizer-based emission reduction target using the criteria for effective targets. This report conducts a review the targets announcement and consultation, Industry repose to the target, and the methodology used to monitor success. This report concludes that while the targets goals of improving efficiency and optimizing nitrogen use are laudable, the measurement use make meeting the target impossible without reductions in nitrogen fertilizer, an action strongly opposed by producers and counter to the targets goal. Lastly the report provides suggestions as to where the methodology could be improved and areas to priorities in the short and long terms to be able to effectively set emission-based targets for 2050.

Keywords: Emission targets, fertilizer-emission, data collection, public policy, 4R

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INTRODUCTION

The Government of Canada (GC) signed the Paris Agreement in 2016 and by doing so, committed to take action towards limiting global warming to well below 2 degrees Celsius (preferably to 1.5 degrees), compared to pre-industrial levels (Environment and Climate Change Canada, 2015). As a signatory to the agreement, Canada is required to submit nationally determined contributions (NDCs) that set out national emission reduction targets (United Nations Framework Convention of Climate Change, 2015). Canada's initial NDC committed to reducing emissions by 30 percent of 2005 levels by 2030 (Government of Canada, 2016, 2017). The NDC has since been updated in 2021 per the Paris Agreement, increasing the emission reduction target to 40-45 percent (Government of Canada, 2021). Accompanying the release of each NDC, the GC has released climate plans outlining how the commitments will be met. Canada's first national climate plan was the Pan-Canadian Framework on Clean Growth and Climate Change (Pan-Canadian Framework), introduced in 2016 (Environment and Climate Change Canada, 2016b). This was followed by the A Healthy Environment and a Healthy Economy (Strengthened Climate Plan) in 2020 and then the 2030 Emission Reduction Plan in 2022 (Environment and Climate Change Canada, 2020, 2022a). Within each plan, actions have been proposed for each sector and generally comprise promises for increased funding and sector-specific emission reduction targets.

Within the Pan-Canadian Framework, Agriculture was largely ignored (Environment and Climate Change Canada, 2016b). No specific emission targets were proposed, and climate actions were limited to increasing stored carbon in agricultural soils, generating bioenergy and bioproducts, and advancing innovation. This changed with the introduction of Canada's Strengthened Climate Plan, as agriculture began to feature more prominently (Environment and Climate Change Canada, 2020). The plan introduced $631 million funding to enhance and restore lands to boost carbon sequestration, including both grasslands and agricultural land. The plan established $98.4 million Natural Climate Solutions for Agriculture Fund and promised the development of a Canadian Agri-Environmental Strategy. It also included a section on Climate-Smart Agriculture which pledged to invest $165.7 million to help develop transformative clean technologies and help farmers adopt clean technologies. Pledges were also made about working with provinces and territories to boost climate-smart practices and increase biofuel production. Lastly, the Strengthened Climate Plan introduced the first climate target for the agricultural sector. Details about the target were not readily available at the time of publication, and the complete text of the proposal read as follows:

> *"Set a national emission reduction target of 30% below 2020 levels from fertilizers and work with fertilizer manufacturers, farmers, provinces and territories, to develop an approach to meet it." (Environment and Climate Change Canada, 2020, p. 45)*

Agriculture and Agri-Food Canada (AAFC) began the public consultation process for the emission reduction target in 2022 with the release of Reducing emissions arising from the application of fertilizer in Canada's agriculture sector discussion document. The document provided essential information about the target, namely what would be included under fertilizer emissions, motivation for the target's development, and identifying several strategies for meeting it (Agriculture and Agri-Food Canada, 2022a).

The document defined Fertilizer emissions as direct and indirect emissions from applying inorganic fertilizer and CO2 emissions from urea and other carbon-containing fertilizers (Agriculture and Agri-Food Canada, 2022a; Fertilizer Canada, 2022a). The target did not include emissions from fertilizer production or organic fertilizer use. Based on 2019 data, AAFC estimated fertilizer emissions equal to 12.75 Mt CO2eq and anticipated the target would require an annual reduction of 4 Mt CO2eq by 2030 (Agriculture and Agri-Food Canada, 2022a).

From the document, there appears to be three primary motivations for developing the target. First are the commitments made under the Paris Agreement, which requires significant absolute reduction in GHG emissions by 2030 (Agriculture and Agri-Food Canada, 2022a), and the Canadian Net Zero Emissions Accountability Act, a domestic commitment for achieving net zero emissions by 2050 (Government of Canada, 2023). For both targets, significant reductions will be required across all sectors of the economy, including agriculture (Environment and Climate Change Canada, 2022a). The second motivation appears to be trends in fertilizer emissions. Nitrogen fertilizer use and the corresponding nitrogen emissions have increased considerably between 2005-2019, increasing by 71 and 54 percent, respectively (Agriculture and Agri-Food Canada, 2022a). Fertilizer use has been the primary driver of increasing emissions from crop production, which have offset reductions in other areas of the sector (Environment and Climate Change Canada, 2022c). The last motivation appears to be how Canada compares internationally. Using data from the FAO Emission intensity Database, AAFC showed that the average emission intensities for cereal production in Canada compared poorly to other major exporting countries (Agriculture and Agri-Food Canada, 2022a). Canadian intensity measurements have increased over time, suggesting substantial room for improvement. The authors of the document the challenges facing the Ag sector as follows:

> *"The defining challenge for Canadian agriculture in the 21st century will be to reduce absolute GHG emissions, and ultimately reach net-zero emissions by 2050, while finding ways to increase yields and economic growth – all while feeding a growing global population." (Agriculture and Agri-Food Canada, 2022a, para. 14)*

The motivations for meeting the defining challenge for Canadian agriculture are evident within the document. It's important to focus on reducing emissions from agriculture sector in order to fulfil our commitments, both internationally and domestically. The growth of emissions in crop production and poor comparison with other major exporting countries makes the source an attractive target for reductions. However, given fertilizer's importance in agricultural production, the goal is not to reduce fertilizer use but to improve efficiency and optimize nitrogen use (Agriculture and Agri-Food Canada, 2022a).

Increasing the adoption of 4R nutrient stewardship practices featured prominently in the discussion document and reflected the target's goals (Agriculture and Agri-Food Canada, 2022a). 4R aims to apply the right nutrient source at the right rate, time, and place to meet nutrient requirements while minimizing potential loss from the field (The Canola Council of

Canada, 2022). Estimates highlighted in the document suggested that widespread adoption of 4R practices in Western Canada alone would account for 50 to 75 percent of the fertilizer target (Agriculture and Agri-Food Canada, 2022a). Enhanced efficiency fertilizer (EENF) adoption was identified as the most effective 4R BMP. AAFC estimated that if full adoption were to occur, this practice would account for more than 50 percent of the fertilizer target, given low current adoption rates, high mitigation potential, and general applicability (Agriculture and Agri-Food Canada, 2022a). Adopting EENFs would not require any reduction in fertilizer use but just nitrogen source changes, making its adoption relatively easy. Other practices highlighted by AAFC included increasing legumes in the rotation, improving drainage, and adopting conservation tillage practices.

The Grain Growers of Canada best-summarized industry responses to the proposed target:

> *"We recognize that you cannot hit what you do not aim at, but such a target must be practical, measurable and achievable, without adverse economic impacts." (Grain Growers of Canada, 2022, p. 2)*

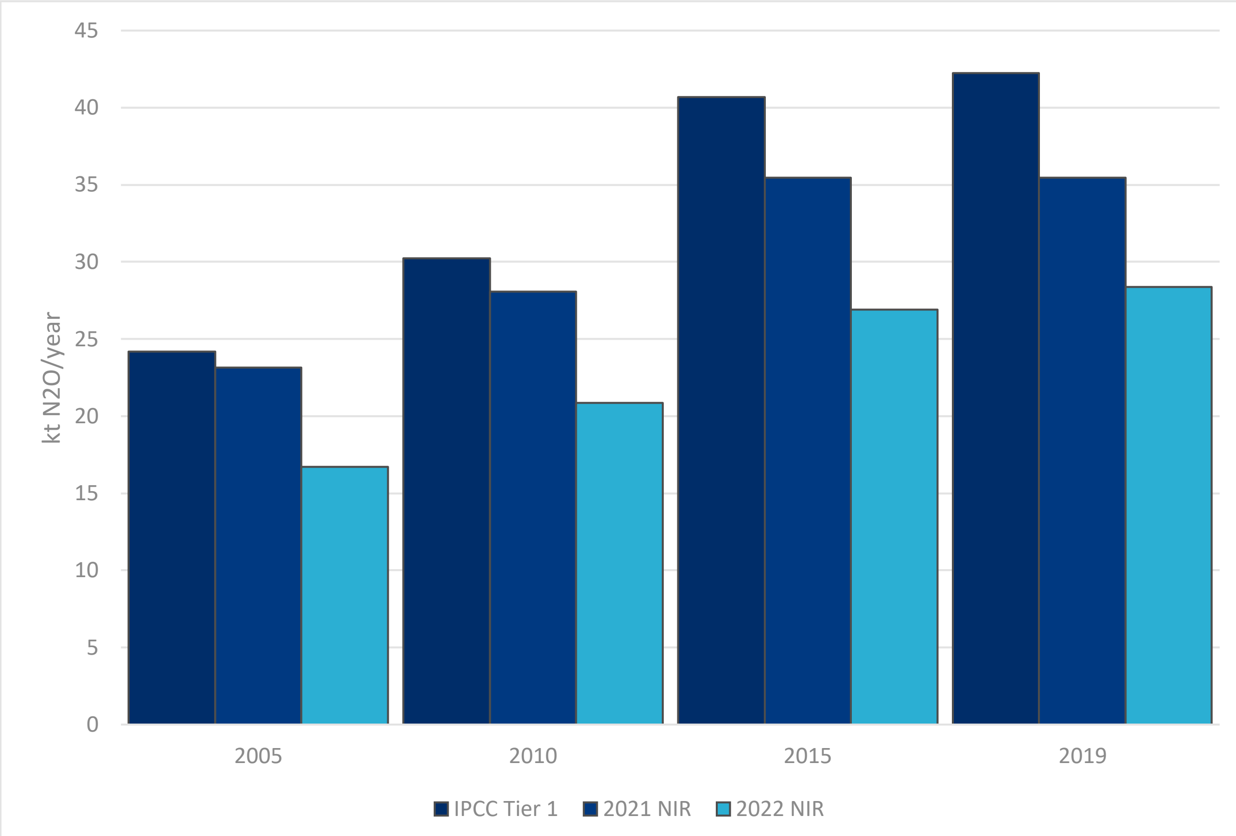
From the responses, there appears to be a clear understanding of the challenges facing the sector. Industry groups acknowledge that climate change is happening and represents a clear hazard to agricultural production and livelihoods (Alberta Wheat and Barley Commissions, 2022; Grain Growers of Canada, 2022; Ontario Federation of Agriculture, 2022). Responses to the target also recognized that improvements could be made by adopting 4R nutrient stewardship and other conservation practices (Alberta Wheat and Barley Commissions, 2022; Canola Council of Canada & Canadian Canola Growers Association, 2022; Fertilizer Canada, 2022a; Grain Growers of Canada, 2022; Ontario Federation of Agriculture, 2022; Sask Crop & Agricultural Producers Association of Saskatchewan, 2022; Team Alberta Crops, 2022; Western Canadian Wheat Growers Association, 2022). However, the target is generally opposed as it is not viewed as practical, measurable, or attainable in the proposed time. There is also a fear that the target will be used to justify a mandatory reduction in fertilizer as 2030 approaches, which industry groups would vehemently oppose (Grain Growers of Canada, 2022; iFusion Research, 2022; Western Canadian Wheat Growers Association, 2022).

While the fertilizer emission target in its current state was generally opposed, the target development was not, and many responses provided alternative targets or metrics (Alberta Wheat and Barley Commissions, 2022; Grain Growers of Canada, 2022; Ontario Federation of Agriculture, 2022; Sask Crop & Agricultural Producers Association of Saskatchewan, 2022; Team Alberta Crops, 2022; Western Canadian Wheat Growers Association, 2022). Target setting is an essential step in the development of public policy. It provides a clear indication of the government's policy objectives and priorities. Targets also provide stakeholders clear policy direction, enabling them to plan, monitor, and deliver on policy objectives. To ensure the effectiveness of targets, they need to be well-defined, measurable, and achievable. However, the proposed target does not appear to meet the criteria, which raises concerns about its feasibility (Fertilizer Canada, 2022b; Grain Growers of Canada, 2022). The lack of details and clarity concerning the target has also led to confusion and anxiety within the sector (Alberta Wheat and Barley Commissions, 2022; Grain Farmers of Ontario, 2022; iFusion Research, 2022). Essential information like the definition of fertilizer emissions was only released with the AAFC discussion document over a year after being proposed. Baseline estimates for 2020 levels were also unavailable until April 2022, indicating that the target development, the release of the AAFC discussion document, and the initial consultations related to the target were done without a clear baseline estimate (Environment and Climate Change Canada, 2022c). Changes made to Canada's official methodology in 2022 resulted in significant recalculations for direct fertilizer-based emissions further increased confusion around the target (Environment and Climate Change Canada, 2022b). The recalculations resulted in emission levels approximately 20 percent below previously estimated levels and substantially different from what was shown in the AAFC discussion document. Although the changes made to the model were undoubtedly an improvement, they created the impression of a moving target because both the baseline value and target were altered. Several of the responses highlighted additional concerns about measurability of the target as many of the mitigation strategies identified are not included within the model (Alberta Wheat and Barley Commissions, 2022; Fertilizer Canada, 2022a; Sask Crop & Agricultural Producers Association of Saskatchewan, 2022). Additionally, from a policy perspective, the absence of BMPs in the national inventory methodology greatly complicates planning and prioritization, as the effects of the practices on estimated emissions are not yet known and will likely change as the model evolves.

CANADIAN METHODOLOGY AND APPLICABILITY TO TARGET SETTING

For non-point source emissions, detailed models are required to estimate emissions as the ability for direct monitoring over large areas is either impractical or impossible. However, the estimation of emission levels and feasibility of emission targets can be significantly impacted by the methodology used, even if the underlying data remains unchanged. The effects are highlighted in Figure 1, which depicts estimates for direct emissions from fertilizer using three internationally accepted approaches, the IPCC Tier 1 Approach and Canada's 2021 and 2022 national inventory methodologies. These differences are critical in formulating emission targets, as the emission levels and mitigation strategies would depend highly on what is included in the model and model assumptions. For example, if Canada used an IPCC Tier 1 approach, emission reductions could only occur if nitrogen use was decreased (IPCC, 2019). This is because emissions are estimated by multiplying total nitrogen use by a set emission factor of 1 percent. This approach is straightforward, transparent, and has a low data requirement. However, the approach comes at the cost of accuracy and applicability to any specific region. The methodology can be improved by estimating a set of regional, environmental, or practice-specific emissions factors or by using more dynamic models (Environment and Climate Change Canada, 2022d; Environmental Protection Agency, 2022).

Figure 1. Canadian Fertilizer-Induced Emission Estimates Using Different Emission Methodologies



Data Source: Emission's data was collected from the 2021 and 2022 Common reporting format (CRF) Tables for the 2021 and 2022 NIR Values (Environment and Climate Change Canada, 2021, 2022b). Nitrogen use data was collected from the 2022 NIR and used use calculate IPCC Tier 1 values following the IPCC Tier 1 Methodology (Environment and Climate Change Canada, 2022b; IPCC, 2019).

Globally, the methodology for estimating fertilizer-based emissions is not robust. Of the 43 countries in 2022 required to provide annual emission estimates to the UNFCCC, only ten have gone beyond the IPCC Tier 1 approach for direct emissions for inorganic fertilizer use, see Annex 1. Table 1 provides an overview of the variables captured in the country-specific (C/S) methodologies. Seven of the ten C/S approaches use set emission factors, which estimate emissions similar to a Tier 1 approach. Set factor methods can be found in varying complexity and include different variables. For example, Germany has estimated specific emissions factors for geographical regions but does not differentiate by fertilizer type or production (Federal Environment Agency, 2022). Ireland uses emission factors specific to inorganic nitrogen types and includes factors for calcium ammonium nitrate, urea, and urea with inhibitor. (Duffy et al., 2022). Australia's approach is the most complex for non-dynamic models as it has different emission factors for land uses, production systems, and specialty crops such as sugar cane and cotton (Australian Government Department of Industry, 2022). The complexity of the methodology increases significantly in the case of the United States (Tier 3), Canada (Tier 2), and the United Kingdom (Tier 2) as they use dynamic models to estimate emissions tied to specific geographical areas and account for both environmental conditions and management practices (Brown et al., 2022; Environment and Climate Change Canada, 2022d; Environmental Protection Agency, 2022).

Table 1: Summary of Country Specific Methodologies for Direct Fertilizer-Induced Emissions

C/S Methods		Included Variables								
		Inorganic N Type	*Nitrogen Inhibitors*	*Land Use*	*Production*	*Weather / Climate*	*Landscape*	*Irrigation*	*Tillage*	*Other Practices*
Set C/S Factors	*AUS*									
	DEU									
	IRL									
	JPN									
	NLD									
	NZL									
	RUS									
Dynamic Factors	*GBR*									
	CAN									
	USA									

Note: Highlighted boxes indicates the country specific model contains related input variables. Data sources can be found in Annex 1.

While the models used by Canada, the United Kingdom, and the United States provide clear advantages to more straightforward C/S methodologies, they are still poorly suited for measuring performance towards the target as available levers for reducing emissions are severely limited. For example, the United Kingdom estimates different emission factors for urea and other inorganic nitrogen sources as a function of application rate and precipitation (Brown et al., 2022). The methodology limits producers with two levers, switching to the lower-emitting source and reducing the application rate. The UK's approach, although more advanced, offers similar levers as those of Ireland, Japan, and New Zealand, where inorganic nitrogen types and nitrogen inhibitors have set emission factor values (Duffy et al., 2022; Greenhouse Gas Inventory Office of Japan and Ministry of the Environment, 2022; Ministry for the Environment, 2022).

Canada's methodology is primarily based on environmental characteristics. The emission factors are estimated using precipitation, potential evapotranspiration, topography, and soil texture data at the eco-district level (Environment and Climate Change Canada, 2022d). The estimated factors are then modified for crop type (annual or perennial) and nitrogen source (organic or inorganic). Emission levels are calculated using a two-step process in which applied nitrogen is multiplied by the emission factor and then modified to account for tillage (conservation or conventional) and irrigation (yes or no). In total, producers' decisions directly affect only five model inputs, crop type, nitrogen source, application rate, tillage, and irrigation.

However, when taking into account the production system, the opportunities for reducing emissions are even more restricted. The technical challenges for meeting the proposed target are apparent when comparing the model to the BMPs highlighted in the AAFC discussion document. As seen in Table 2, only three of the eleven BMPs highlighted in the discussion document are directly incorporated into the methodology. Four highlighted BMPs can potentially affect emission estimates if total nitrogen sales are decreased, but the full effect on emissions is unlikely to be captured. Lastly, the model does not include practices such as enhanced efficiency fertilizer use, spring application of nitrogen, fertigation, and improved field drainage. These four practices account for 55 percent of total mitigation potential (Agriculture and Agri-Food Canada, 2022a). Without their inclusion, the target is unobtainable without significant decreases in fertilizer use.

Table 2: Information on the Beneficial Management Practices Identified in the AAFC Discussion Document

Beneficial Management Practices	Regional Applicability	Current Adoption Level	Mitigation Potential (%)	Mitigation Potential (Mt CO2e /yr)	Included in Methodology
Annual Soil Testing + Spring Application	All Regions	Low	5-15%	0.23	Indirectly Included
Nitrogen Credit (legume crop)	All Regions	Medium/High	10-20%	0.63	Indirectly Included
Spring Application	Mainly West	High	5-15%	0.12	Not Included
Fertigation	Mainly West	Low	15-25%	0.02	Not Included
Split Application + Sensor Adjusted Rate	Mainly East	Medium	15-35%	0.65	Indirectly Included
Bands/Injection + Reduced Rate	All Regions	High (W) Medium (E)	5-15%	0.24	Indirectly Included
EENF USE	All Regions	Very Low	15-35%	2.35	Not Included
Organic Fertilizer Use	All Regions	Low	10-20%	0.15	Included
Conservation Tillage	All Regions	High (W) Medium (E)	5-15%	0.15	Included
Improved Drainage Design	Mainly East	Medium/High (E)	10-30%	0.13	Not Included
Increasing legumes in Rotations	Mainly West	Low	15-25%	0.1	Included

Note: Adapted from "Discussion document: Reducing emissions arising from the application of fertilizer in Canada's agriculture sector", by Agriculture and Agrifood Canada, 2022, February. Retrieved from: https://agriculture.canada.ca/en/department/transparency/public-opinion-research-consultations/share-ideas-fertilizer-emissions-reduction-target/discussion. W indicated adoption in Western Canada, E indicated adoption in Eastern Canada. Mitigation Potential measured in Mt CO2e /yr assumes 100 percent adoption in applicable areas. Indirectly included within the methodology indicated that the practices will result in measurable emission reduction if it results in decreased sales at the provincial level.

NATIONAL INVENTORY MODEL INPUTS

Direct fertilizer emissions in Canada are estimated at the ecodistrict level (Environment and Climate Change Canada, 2022d). Eco-districts are a subdivision of the ecoregions and part of the Ecological Framework of Canada (Agriculture and Agri-Food Canada, 2013). Ecodistrict have a minimum size of 100,000 hectares and are characterized by relatively homogeneous physical, biological, and environmental conditions. When compared to other dynamic models, the use of eco-districts provides a relatively low-resolution estimate. For example, the United Kingdom estimates emissions on a ten-kilometer grid system (10,000 ha) (Brown et al., 2022), while the United States estimates emissions at the field level (Environmental Protection Agency, 2022). To effectively quantify field-level activity, estimates will likely need to be made at the field level. The most significant barrier to obtaining this level of resolution is data availability, not methodology. Model inputs can be divided into three broad categories: landscape, weather, and management practice variables (Environment and Climate Change Canada, 2022d). A complete description of each model input and the scale and frequency of the data can be found in Table 3.

Landscape Variables: The fraction of the eco-district occupied by depressions and the weighted average of soil texture within the ecodistrict are the two landscape variables included within the model and are used to estimate the base emission factor. Data for both variables originate from Soil Landscapes Canada (SLC) and are available at a scale of 1:1 million (Agriculture and Agri-Food Canada, 2021). At the field level, SLC data is not spatially explicit; however, SLC polygon or eco-district averages may be appropriate for field-level estimates if higher resolution data is unavailable.

Weather Variables: Growing Season Precipitation and Potential Evapotranspiration are the two weather variables included within the model and are used in estimating the base emission factor (Environment and Climate Change Canada, 2022d). For both weather variables, historic 30-year averages are used, covering a period from May 1st to October 31st and from 1971 to 2000. The data originates from a network of weather stations across Canada and the United States which were used to interpolate weather conditions to the ecodistrict centroid. This approach can estimate weather conditions at any point and may be appropriate for field-level estimates.

Table 3. Model Input Variables for Direct Fertilizer-Induced Emissions from Annual Crop Production

Variable Type	Variable	Description	Scale	Frequency	Source
Landscape	*Topography*	Fraction of the area of ecodistrict i that is in the lower section of the toposequence	Ecodistrict	Static Estimate	Soil Landscapes of Canada
	Soil Texture	Weighted soil texture ratio factor of N_2O for ecodistrict i	Ecodistrict	Static Estimate	Soil Landscapes of Canada

Weather	*Precipitation*	Long-term mean precipitation from May 1 to October 31 for ecodistrict i	Point Estimate	1971 - 2000	Meteorological Service of Canada, ECCC

	Potential Evapotranspiration	long-term mean potential evapotranspiration from May 1 to October 31 for ecodistrict i	Point Estimate	1971 - 2000	Meteorological Service of Canada, ECCC
Management Practices	*Conservation Tillage*	fraction of cropland on NT and RT in ecodistrict i	Ecodistrict	Census Years	Census of Agriculture
	Irrigation	fraction of irrigated cropland in ecodistrict i	Ecodistrict	Census Years	Census of Agriculture
Management Practices: Nitrogen Use	*Nitrogen Sales*	total amount of fertilizer N sold in province p, kg	Provincial	Annual	Statistics Canada
	Nitrogen Recommendation	recommended annual N application rate for crop type j in ecodistrict i, kg N ha yr-1	Provincial	Static Estimate	Yang et al. (2007)
	Crop Production	area of crop type j in ecodistrict i, ha	Ecodistrict	Census Years	Census of Agriculture

Note: Landscape variable descriptions were directly copied from Equation A3.4-12 from the National Inventory Report 1990-2020: Greenhouse Gas Sources and Sinks in Canada Part 2 produced by ECCC. The descriptions for the nitrogen use variables were from Equation A3.4-19 and A3.4-20. Variable descriptions for Management Practices were from Equation A3.4-28 and A3.4-29. Information on the Scale Frequency and Source where also from the 2022 National Inventory Report (Environment and Climate Change Canada, 2022d)

Both the landscape and weather variables use constant values (Environment and Climate Change Canada, 2022d). As a result, the estimated base emission factor does not change yearly. This approach simplifies data collection and analysis as values are only calculated once per ecodistrict. It also allows for more predictable estimates, as changes in emissions solely cause changes in practices. However, using constant values introduces a large amount of uncertainty in the annual estimates. Canada's methodology uses an exponential function to relate growing season precipitation to the emission factor estimate (Environment and Climate Change Canada, 2022d). As a result, small changes in growing season precipitation can result in significant variations in annual emissions. Even if annual variation is not a concern, changing rainfall patterns, increasing average temperatures, and more frequent extreme weather events are occurring due to climate change in Canada (Environment and Climate Change Canada, 2016a, 2022e). These changes suggest that the weather variable’s distribution and average values have changed from the 1971 to 2000 average, and at the very least, the values should be updated. Moving from the long-term average would also bring the approach more in line with the United Kingdom and the United States, which use annual estimates at a higher spatial resolution (Brown et al., 2022; Environmental Protection Agency, 2022).

Management Practice Variables: Spatially explicit data related to management practices and nitrogen use is needed for estimating emissions that can be used for target setting. This is because the mitigation potential of BMPs depends not only on the land's environmental and physical characteristics but also on what other practices are adopted (Bourassa et al., 2022). For example, 4R entails applying the right source at the right time, place, and rate. Determining what is considered "right" would require data on the other 4R components, information on production, and the environmental and soil conditions specific to the field (The Canola Council of Canada, 2022). Currently, the data used for estimating fertilizer-induced emissions is not at the level required for monitoring emission-based targets. Production, irrigation, and tillage data originates from the Census of Agriculture (Environment and Climate Change Canada, 2022d). While the census provides a comprehensive snapshot of Canadian agriculture, it is only conducted on a 5-year cycle and is not spatially explicit to the required level (Statistics Canada, 2023b). As seen in Table 4, the 2021 Census of Agriculture did not collect information on the adoption rates of all management practices identified in the discussion document, however a combination of both the Census and Farm Management Survey may be able to partially cover most practices (Statistics Canada, 2022b, 2022d). Given the frequency of both surveys, baseline adoption rates are unlikely to be fully available until 2026, and changes to the levels would be unavailable until 2031 (Statistics Canada, 2023b).

Data related to inorganic fertilizer use at the eco-district level is based on provincial-level fertilizer sales data, availability of organic nitrogen sources, and fertilizer use recommendations (Environment and Climate Change Canada, 2022d). A recommended nitrogen application level is first calculated for the eco-district by multiplying the total area for each crop type grown by its corresponding application rate based on estimates from Yang et al. (2007). Total organic nitrogen with the ecodistrict is then subtracted from the recommended amount (Environment and Climate Change Canada, 2022d). Lastly, total nitrogen sales are allocated to each ecodistrict based on the district's share of the provincial recommended amount. While this approach provides a back-of-the-envelope calculation for nitrogen use within the ecodistrict, it still cannot fully reflect changes in fertilizer use at the ecodistrict level.

Table 4: Questions from the Census of Agriculture and FMS on the Beneficial Management Practices Identified in the AAFC Discussion Document

Beneficial Management Practices	Census of Agriculture	Census Question	Farm Management Survey	FMS Questions
Annual Soil Testing + Spring Application	Partially Collected	In 2020, were the following technologies used on this operation? (Soil sample test. Yes/No)	Partially Collected	Considering all land used for [field/forage] crop production on this operation, how often is the soil tested for nutrient content?
Nitrogen Credit (legume crop)	Partially Collected	In 2020, were the following technologies used on this operation? (Soil sample test. Yes/No)	Partially Collected	Considering all land used for [field/forage] crop production on this operation, how often is the soil tested for nutrient content?
Spring Application	Not Collected		Collected	During [Time Period], what application method was used for commercial fertilizer?
Fertigation	Not Collected		Collected	In 2021, what application method was used for commercial fertilizer applied after seeding?
Split Application + Sensor Adjusted Rate	Partially Collected	In 2020, were the following technologies used on this operation? (Variable-rate input application Include variable-rate seeders, sprayers and fertilizer applications. Yes/No)	Partially Collected	During [Time Period], what application method was used for commercial fertilizer?
Bands/Injection + Reduced Rate	Not Collected		Partially Collected	During [Time Period], what application method was used for commercial fertilizer?
EENF USE	Partially Collected	In 2020, were the following technologies used on this operation? (Slow-release fertilizer. Yes/No)	Collected	Between October 2020 and September 2021, which of the following products were applied to [selected crops]?

Beneficial Management Practices	Census of Agriculture	Census Question	Farm Management Survey	FMS Questions
Organic Fertilizer Use	Collected	In 2020, what was the area on which each of the following inputs or manure were used on this operation?	Collected	Multiple Questions
Conservation Tillage	Collected	In 2021, what is the area on which the following tillage and seeding practices will be used on land seeded or to be seeded?	Collected	For all croplands on this operation, please indicate the area of land that was managed using each of the following tillage systems.
Improved Drainage Design	Not Collected		Collected	Over the last five years, 2017 to 2021, which of the following land management improvements were implemented or installed on this operation?
Increasing legumes in Rotations	Collected	In 2021, what is the area on this operation of each of the following hay or field crops?	Collected	Please list the sequence of field crops for a rotation. If there is more than one rotation used on this operation, provide the sequence of the three most common rotations.

Note: Census Questions were copied from the 2021 Census of Agriculture, produced by Statistics Canada and retrieved from https://www.statcan.gc.ca/en/statistical-programs/instrument/3438_Q1_V6. Farm Management Survey Questions were copied from the 2021 Farm Management Survey Crop Modules produced by Statistics Canada and retrieved from https://www.statcan.gc.ca/en/statistical-programs/instrument/5044_Q1_V2. "Not Collected", "Partially Collected", and "Collected" where subjective classification as to how well the survey questions captured the management practice. "Partially Collected" indicted that part of the practice was included within the question. For example: Annual Soil Testing + Spring Application was partially collected in the Census of Agriculture because there were questions related to soil testing but did not include questions that would account for both practices. EENF use was only partially collected because the survey questions asked about slow-release fertilizers but not nitrogen inhibitors (Statistics Canada, 2022d).

NEAR-TERM PRIORITIES

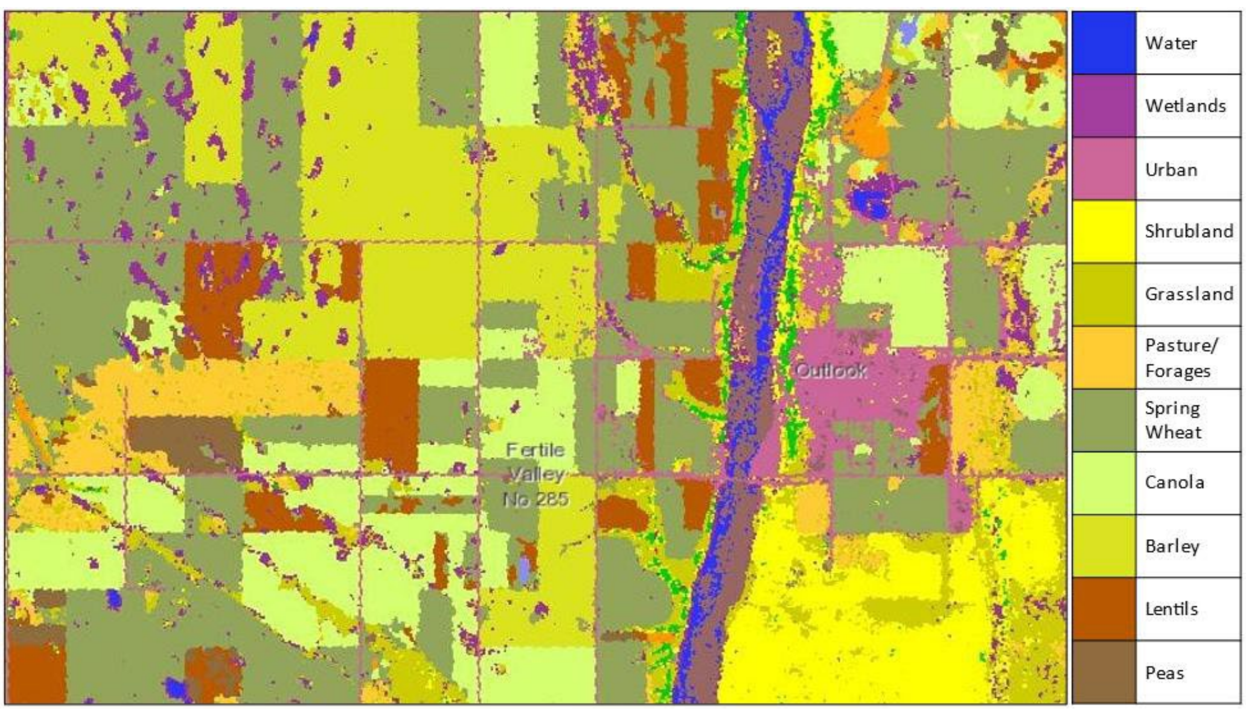
Significant improvements to the methodology and data are needed to make the proposed fertilizer emission target operational. However, achieving the target's goal of optimizing nitrogen use and improving efficiency can be accomplished without measurable emission reductions. Meeting the proposed target will require a significant increase in the adoption of various beneficial management practices. Clearly identifying current field-level activity, developing strategies to increase the adoption of BMPs, and monitoring adoption-level changes can achieve the same goals as an emission target while greatly simplifying the process. Additionally, any improvement to the methodology will require better data at a higher resolution than what is currently available. As a result, improvements in data collection should be prioritized.

Farm management data may not need to come directly from traditional sources like the Census of Agriculture. Both federal and provincial organizations should be encouraged to experiment with data collection strategies to better understand the producers' willingness to share on-farm information, what information is readily available, and potential barriers. At the federal level, changes to the Farm Management Survey (FMS) may be a practical starting point. The survey is designed to build on information collected in the Census of Agriculture; it is conducted every 5 years and has a total sample size of 18,000 farms (Statistics Canada, 2022a). Increasing the scale from farm to field level and increasing sampling frequency to biennial or annual may provide the required information within an existing framework. At the provincial level, agricultural benchmarking surveys could be expanded to include additional information on fertilizer management. Increasing the size and scope of programs like Alberta's AgriProfit$ survey could benefit policymakers and producers as the quality of the benchmark would increase and provide better insight into the cost and benefits of different mitigation practices (Alberta Agriculture and Irrigation, 2023). Other strategies could focus on increasing reporting requirements when purchasing crop insurance or providing tax incentives for sharing data with provincial or federal organizations.

Annual representative farm surveys are used in the United Kingdom and the United States to obtain the required data for their emission estimates (Brown et al., 2022; Environmental Protection Agency, 2022). The scale of the surveys and the information collected vary considerably and provide an idea of the data requirements for different measurement options. The United States uses data from the National Resource Inventory (NRI) survey to estimate emissions (Environmental Protection Agency, 2022). The NRI comprises a sample of 349,464 points (field-level observations) which are then scaled to the entire country using what is referred to as an expansion factor for areas covered under their Tier 3 model. The United Kingdom uses the British Survey of Fertilizer Practices (BSFP) and the Farm Business Survey (FBS) to estimate nitrogen application rates for different crop and grassland types (Brown et al., 2022). The application rates are used to estimate both the emission factors and total nitrogen use within each ten-kilometer grid square. A Canadian version of a BSFP or FBS could be developed to provide regionally representative estimates of nitrogen use and adoption rates of beneficial management practices. A survey of this scale would be effective at for setting and monitoring progresses toward a target based on adoption rates. An annual survey at the scale of the NRI would likely be required to meet the data requirements for a Tier 3 estimate or monitoring progress towards an emission-based target.

Improvements in remote sensing technology and spatial analysis techniques have significantly increased the accessibility of high-resolution spatially explicit data. Adopting new and better data sources could improve the accuracy of current estimates even without changes to the current methodology. For example, digital elevation maps combined with spatially explicit crop inventory data would allow for field-level estimates if soil texture is assumed to be constant within the SLC polygon. Canada's High-Resolution Digital Elevation Model (HRDEM), produced by Natural Resource Canada, is available at up to a meter resolution and with coverage across Canada (Natural Resources Canada, 2022). The HRDEM could be used to provide field-level topographical data for emission estimates instead of using the fraction of the depressional area for the ecodistrict. AAFC's Annual Crop Inventory could identify the total area by crop type within the eco-district more frequently than the ag census or used in field-level estimates. The inventory utilizes satellite imagery to identify land use and major crop types at a 30-meter resolution (Agriculture and Agri-Food Canada, 2023). Higher resolution data can help ensure that only agricultural land is included in the estimate. For example, depressional land may not be seeded if it is expected to remain saturated throughout the growing season, see Figure 2. Spatial data could also be differentiated between dryland and irrigated production to better account for crop types and practices differences. Research in the United States has leveraged publicly available satellite imagery to create accurate irrigation maps at a 30-meter resolution (Ketchum et al., 2020). Given proximity and production similarities, if this approach is taken in Canada, the models developed in the United States, maybe applicable to a Canadian setting.

Figure 2: Sample Image from AAFC's Annual Crop Inventory



Note: Image from the 2018 Annual Crop Inventory produced by the Earth Observation Team of the Science and Technology Branch at AAFC (2019), and retrieved from https://hub.arcgis.com/datasets/f0ec9248e7bc4174965c3dbab5b2ce67/explore. The Image was taken in the vicinity of Outlook Saskatchewan at coordinates 51 ° 29’ 20” N, 107 ° 03’ 31” W.

REACHING 2050 AND BEYOND

Improving Canada's methodology will be essential for tracking progress toward Canada’s long-term emission goals. For the methodology to be developed on time, long-term planning and coordination of research is required. Rochette et al. (2018) developed the approach to estimate the fertilizer induced N2O emission factors used in the 2022 NIR (Environment and Climate Change Canada, 2022d). The research used a meta-analytical method for estimating the relationships between soil, climate, management practices, and N2O emissions (Rochette et al., 2018). The meta-analysis included a total of 54 studies comprising 1026 data points. Each of the individual studies provides important contributions to the literature and helped provide the foundational research to understand fertilizer induced N2O emission in Canada. However, a lack of standardized data reporting meant that not all observations had the required data for the full analysis. As a result, most studies included in the meta-analysis were unusable in developing the emission factor calculation (Rochette et al., 2018). This could have been partially avoided with better long-term planning and coordination. With long-term planning, potential secondary uses of the data collected and the need for a standardized reporting process could have been identified and allowed for the use of data beyond the initial. AAFC is well positioned and the logical choice to lead the planning and coordination activities, given their involvement in funding and conducting primary agricultural research in Canada. Of the 54 studies included in Rochette et al. (2018), 29 were funded by AAFC, and 40 had authors associated with AAFC, see Table 5. Additionally, almost all research occurred at or near an AAFC research facilities suggesting that the collaboration between research locations is likely. Future developments in Canada's emission methodology will likely go beyond the database assembled by Rochette et al. (2018). Improvements to the methodology would likely require dozens of studies across Canada to generate relevant data. Effective planning and coordination will be essential for long-term success in the methodology's development. A failure to do so would decrease the pool of available research and likely increase the time and cost required to develop the methods.

The studies included in Rochette et al. (2018) were also disproportionately concentrated in Eastern Canada. For the data points used in the analysis, Quebec alone accounted for 56 of the 58 organic and 91 of 171 inorganic nitrogen data points. In contrast, data points from Prairie Canada only included 48 of the 171 inorganic observations despite accounting for over 80 percent of total agricultural land and 82 percent of inorganic nitrogen use in Canada (Statistics Canada, 2022c, 2023a). Improving the geographical distribution of research in Canada is essential for accurately representing variation across Canada in the methodology. While developing a national methodology will inevitably be a federal responsibility, provincial organizations should be heavily involved in encouraging and funding research within their respective provinces. Provincial involvement was not common; only 13 of the studies in Rochette et al. (2018) were funded by provincial governments, see Table 5 and Annex 2. Research coordination between multiple funding sources also appeared lacking with only 8 receiving funding from federal and provincial organizations. Provincial funding could also be used to better encourage studying regional practices that are not widely used. For example, research on the effects of irrigation on fertilizer induced N2O emissions is limited in Canada, leading to broad assumptions used in the emission estimates (Environment and Climate Change Canada, 2022d; Liang et al., 2020). Given the potential impact on national emission levels, this irrigation research may not be a federal priority. However, given Alberta's total irrigated acres and share of irrigated land, methodology improvements could significantly impact provincial-level emission estimates (Statistics Canada, 2021, 2022c).

Table 5: Summary of the Studies used in the meta-analysis by Rochette et al. (2018)

Location	Number of Studies	Data Points			AAFC		Funding						
		Total	*Inorganic*	*Organic*	*Facilities*	*Research*	*Federal*	*AAFC*	*Provincial*	*Producer*	*Other*	*Fed+Prov*	*NA*
BC	2	44	0	0	2	2	2	2	0	0	0	0	0
Prairies	18	513	48	0	4	12	6	6	6	1	2	1	5
ON	14	169	22	2	6	9	11	8	4	1	1	4	3
QC	17	227	91	56	9	14	14	10	0	1	2	0	3
NB	3	12	10	0	2	3	0	3	3	3	0	1	3
Total	54	1026	171	58	23	40	37	29	13	3	7	8	12

Note: Full list of papers can be found in Annex 2. Adopted from "Soil nitrous oxide emissions from agricultural soils in Canada: Exploring relationships with soil, crop and climatic variables.", by Rochette, P., Liang, C., Pelster, D., Bergeron, O., Lemke, R., Kroebel, R., MacDonald, D., Yan, W., & Flemming, C., 2018, Agriculture, Ecosystems and Environment, 254, 71. AAFC research facilities indicates that 1 or more of the field studied was located at an AAFC research facility. AAFC Research was used to identify if 1 or more of the studies authors was affiliated with AAFC at the time of publication. Federal funding includes AAFC and other federal funding sources such as NSERC. NA was used to identify studies that did not disclose funding sources within the paper.

CONCLUSION

Canada uses Tier-2 methodology to estimate baseline fertilizer emissions and emissions reduction through BMP adoption. It does not include EENFs as input variable rendering the proposed target unachievable without drastic reductions in nitrogen fertilizer use. Significant improvements to farm data collection and the development of a Tier 3 emission methodology would be required to make the target operational. Making the necessary improvements by 2030 is unrealistic, but progress toward improving efficiency and optimizing nitrogen use can be made. Developing targets and policies to increase BMP adoption and 4R certification could effectively meet the current target's goals without a detailed emission methodology. Adoption-based targets would still require substantial improvement for data collection to be operational. These improvements can be made relatively quickly by developing representative farm surveys. Data collection needs to be prioritized in the short run as a better understanding of on-farm activity and nitrogen use across varying production systems and regions of Canada is needed for effective policy development and future target setting. Once baselines are identified, well-defined, measurable, and achievable adoption-based targets are realistic and should be adopted to ensure policy goals are met.

Achieving net zero by 2050 will require the development of emission-based targets. Developing effective emission-based targets will require the development of a Tier 3 emission methodology at a scale similar used by the United States. The model will require substantial improvements to data collection, but as discussed, these changes can be made relatively quickly. The research is the major challenge for developing a Tier 3 methodology. The previous iteration of Canada's national inventory methodology is based on decades of academic work. Creating a new approach will require substantial investment and effective coordination and planning if it is to be completed in a timely manner. Developing new funding sources aimed explicitly at quantifying emissions and the effects of BMP adoption would be a logical first step. Actions should also be taken to standardize experimental design and implement requirements on standardized data reporting to ensure that the data collected is usable beyond the initial paper.

The spatial distribution of research in Canada also needs to be greatly improved. As seen in Rochette et al. (2018), research related to fertilizer-induced emissions has been heavily concentrated in Quebec, despite only accounting for five percent of total farmland and six percent of inorganic nitrogen use (Statistics Canada, 2022c, 2023a). Efforts must also be made to conduct research outside traditional research clusters such as Agassiz, Lethbridge, Guelph, and Quebec City to increase the variation in soil and environmental conditions. Canadian researchers are more than capable of producing the work required for developing a Tier 3 model for fertilizer induced N2O emissions. However, a clear plan for conducting the research and coordination between federal and provincial organizations, universities, and colleges will be required for the model development to succeed.

The Government of Canada must take a central role in agri-environmental policy development, research planning and coordination, and data collection if their long-term objectives are to be met. However, given the variation in climate and production across the country, a one size fits all approach is unlikely to be effective. Provincial governments and organizations should be encouraged to develop regional solutions to meet national objectives, with the GC providing coordination and support. For example, a made-in-Alberta strategy will likely focus on large-scale grain and oil seed production for dryland and irrigated production systems. Recommended BMPs, current levels of adoption, and barriers to increasing adoption will likely differ from those developed for Quebec or PEI. Provincial targets may also receive greater buy-in as regional differences and producer concerns are more likely to be reflected in regional targets than at the national level. Provincial organizations also have a role in funding research. Provincial-level funding was rare with the studies included within Rochette et al. (2018), which may have helped contribute to the concentration of research occurring in Eastern Canada, where a majority of AAFC research facilities are located (Agriculture and Agri-Food Canada, 2022b). Increased provincial funding, particularly in the Prairie provinces, would help ensure a more geographically dispersed body of research and to ensure regional practices like irrigation are accurately represented within the models. The Government of Canada's first attempt at developing an emission target for the Ag sector cannot be viewed as a success by any measure. However, the attempt has drawn much-needed attention to data collection and emission methodology issues. Developing operational emission targets for 2030 is highly unlikely, but if the required improvements are made, well-defined, measurable, and achievable targets for 2050 are possible.

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ANNEX 1

Table 6: List of Annex I Parties to the UNFCCC and Models used for Fertilizer Induced Emissions

Country	N_2O	AV	LRO	Urea	Source
Australia	C/S Tier 2	CS	Tier 1*	Tier 1	https://unfccc.int/documents/478957
Austria	Tier 1	CS	CS	Tier 1	https://unfccc.int/documents/461938
Belarus	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461960
Belgium	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461915
Bulgaria	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461950
Canada	C/S Tier 2	C/S	C/S	Tier 1	https://unfccc.int/documents/461919
Croatia	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461772
Cyprus	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461671
Czechia	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461895
Denmark	Tier 1	C/S	Tier 1	Tier 1	https://unfccc.int/documents/461943
Estonia	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461808
Finland	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461893
France	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461899
Germany	C/S Tier 2	C/S	Tier 1	Tier 1	https://unfccc.int/documents/461930
Greece	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461961
Hungary	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461959
Iceland	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/614626
Ireland	C/S Tier 1	C/s	Tier 1	Tier 1	https://unfccc.int/documents/461723
Italy	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461788
Japan	Tier 2	Tier 1*	Tier 1*	Tier 1	https://unfccc.int/documents/461933
Kazakhstan	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461955

Country	N_2O	AV	LRO	Urea	Source
Latvia	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461908
Liechtenstein	Tier 1	C/S	Tier 1	Tier 1	https://unfccc.int/documents/461901
Lithuania	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461952
Luxembourg	Tier 1	C/S	Tier 1	Tier 1	https://unfccc.int/documents/461887
Malta	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461748
Monaco					https://unfccc.int/documents/461822
Netherlands	C/S Tier 1	C/S	C/S	Tier 1	https://unfccc.int/documents/461906
New Zealand	C/S Tier 1	C/S	C/S	Tier 1	https://unfccc.int/documents/461878
Norway	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461706
Portugal	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461818
Romania	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461892
Russian Federation	C/S Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461970
Slovakia	Tier 1	Tier 1	C/S	Tier 1	https://unfccc.int/documents/461882
Slovenia	Tier 1	C/S	Tier 1	Tier 1	https://unfccc.int/documents/461953
Spain	Tier 1	Tier 1	C/S	Tier 1	https://unfccc.int/documents/461784
Sweden	Tier 1	C/S	C/S	Tier 1	https://unfccc.int/documents/461776
Switzerland	Tier 1	C/S	Tier 1	Tier 1	https://unfccc.int/documents/461903
Türkiye	Tier 1	Tier 1	Tier 1	Tier 1	https://unfccc.int/documents/461926
Ukraine	Tier 1	C/S	Tier 1	Tier 1	https://unfccc.int/documents/476868
United Kingdom	C/S Tier 2	C/S	C/S	Tier 1	https://unfccc.int/documents/461922
United States	C/S Tier 3	C/S	C/S	Tier 1	https://unfccc.int/documents/461948

*Note: N2O denotes direct fertilizer-induced emissions. AV denotes volatilization and redeposition of Nitrogen (indirect emission). LRO denotes leaching and runoff (indirect emission). Urea denotes CO2 emissions from liming and urea fertilization. Tier 1 indicates the country use an IPCC Tier 1 approach. C/S indicates a country specific approach. * Indicated the country is explicitly using the methodology from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories instead of the 2006 IPCC Guidelines.*

ANNEX 2

Table 7: Supplementary information for Table 5

Citation	Data Points			Location		AAFC Affiliation		Funding						
	Total	Inorganic	Organic	Prov	Location / Cluster	Location	Researcher	Federal	AAFC	Provincial	Producer	Other	Fed+Prov
Bhandral, R., Bittman, S., Kowalenko, G., Buckley, K., Chantigny, M. H., Hunt, D. E., ... & Friesen, A. (2009). Enhancing soil infiltration reduces gaseous emissions and improves N uptake from applied dairy slurry. Journal of environmental quality, 38(4), 1372-1382.	30	0	0	BC	Agassiz	Yes	Yes	Yes	Yes	No	No	No	No
Bhandral, R., Bittman, S., Kowalenko, C. G., Friesen, A., & Hunt, D. E. (2008). Emissions of nitrous oxide after application of dairy slurry on bare soil and perennial grass in a maritime climate. Canadian Journal of Soil Science, 88(4), 517-527.	14	0	0	BC	Agassiz	Yes	Yes	Yes	Yes	No	No	No	No
Burton, D. L., Li, X., & Grant, C. A. (2008). Influence of fertilizer nitrogen source and management practice on N2O emissions from two Black Chernozemic soils. Canadian Journal of Soil Science, 88(2), 219-227.	42	0	0	MB	Winnipeg, Brandon	No	Yes	Funding not Disclosed					
Chang, C., Janzen, H. H., & Cho, C. M. (1998). Nitrous oxide emission from long-term manured soils. Soil Science Society of America Journal, 62(3), 677-682.	4	0	0	AB	Lethbridge	Yes	Yes	Funding not Disclosed					
Corre, M. D., Pennock, D. J., Van Kessel, C., & Kirkelliott, D. (1999). Estimation of annual nitrous oxide emissions from a transitional grassland-forest region in Saskatchewan, Canada. Biogeochemistry, 44, 29-49.	6	0	0	SK	Unk			Yes	Yes	No	No	No	No

Ellert, B. H., & Janzen, H. H. (2008). Nitrous oxide, carbon dioxide and methane emissions from irrigated cropping systems as influenced by legumes, manure	27	0	0	AB	Lethbridge	Yes	Yes	Yes	Yes	No	No	No	No

Citation	Data Points			Location		AAFC Affiliation		Funding					
	Total	Inorganic	Organic	Prov	Location / Cluster	Location	Researcher	Federal	AAFC	Provincial	Producer	Other	Fed+Prov
and fertilizer. Canadian Journal of Soil Science, 88(2), 207-217.													
Guerin, J.E, Lemke, R, Goddard, T.W, & Sprout, C. (Unpublished) Tillage System and Summerfallow Effects on Nitrous Oxide Emissions on a Udic Boroll Soil on the Canadian Prairies							Unpublished						
Hao, X., Chang, C., Carefoot, J. M., Janzen, H. H., & Ellert, B. H. (2001). Nitrous oxide emissions from an irrigated soil as affected by fertilizer and straw management. *Nutrient Cycling in Agroecosystems*, *60*, 1-8.	6	0	0	AB	Lethbridge	Yes	Yes	No	No	Yes	No	No	No
Izaurralde, R. C., Lemke, R. L., Goddard, T. W., McConkey, B., & Zhang, Z. (2004). Nitrous oxide emissions from agricultural toposequences in Alberta and Saskatchewan. *Soil Science Society of America Journal*, *68*(4), 1285-1294.	13	0	0	AB, SK	Mundare, Swift Current	No	Yes	Yes	Yes	No	No	Yes	No
Lemke, R., Farrell, R., Brandt, S., Lafond, G., Malhi, S.S., & Wang, Z.H. (Unpublished). The Influence of Nitrogen Fertilizer Placement, Timing and Formulation on Nitrous Oxide Emissions from Four Locations in Saskatchewan	37	0	0				Unpublished						
Lemke, R. L., Izaurralde, R. C., Malhi, S. S., Arshad, M. A., & Nyborg, M. (1998). Nitrous oxide emissions from agricultural soils of the Boreal and Parkland regions of Alberta. *Soil Science Society of America Journal*, *62*(4), 1096-1102.	8	0	0	Ab	Breton, Edmonton, Eckville, Rycoft	No	Yes			Funding not Disclosed			

Citation	Data Points			Location		AAFC Affiliation		Funding						
	Total	Inorganic	Organic	Prov	Location / Cluster	Location	Researcher	Federal	AAFC	Provincial	Producer	Other	Fed+Prov
Lemke, R. L., Izaurralde, R. C., Nyborg, M., & Solberg, E. D. (1999). Tillage and N source influence soil-emitted nitrous oxide in the Alberta Parkland region. *Canadian Journal of Soil Science*, *79*(1), 15-24.	32	0	0	AB	Edmonton, Breton	No	Yes	Yes	Yes	No	No	No	No
Lemke, R. L., Zhong, Z., Campbell, C. A., & Zentner, R. (2007). Can pulse crops play a role in mitigating greenhouse gases from North American agriculture?. *Agronomy Journal*, *99*(6), 1719-1725.	26	0	0	AB, SK	Three Hills, Swift Current	No	Yes	Funding not Disclosed					
Lemke, R., Farrell, R., Brandt, S., Lafond, G., Malhi, S.S., & Wang, Z.H. (Unpublished). The Influence of Nitrogen Fertilizer Placement, Timing and Formulation on Nitrous Oxide Emissions from Four Locations in Saskatchewan	120	0	0	Unpublished									
Malhi, S. S., & Lemke, R. (2007). Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emissions in a second 4-yr rotation cycle. *Soil and Tillage Research*, *96*(1-2), 269-283.	32	0	0	SK	Star City	No	Yes	No	No	Yes	No	No	No
Malhi, S. S., Lemke, R., & Schoenau, J. J. (2010). Influence of time and method of alfalfa stand termination on yield, seed quality, N uptake, soil properties and greenhouse gas emissions under different N fertility regimes. *Nutrient cycling in agroecosystems*, *86*, 17-38.	9	0	0	SK	Star City	No	Yes	No	No	Yes	No	No	No
Malhi, S. S., Lemke, R., Wang, Z. H., & Chhabra, B. S. (2006). Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. Soil and Tillage Research, 90(1-2), 171-183.	16	0	0	SK	Star City	No	Yes	No	No	Yes	No	No	No

Citation	Data Points			Location		AAFC Affiliation		Funding					
	Total	*Inorganic*	*Organic*	*Prov*	*Location / Cluster*	*Location*	*Researcher*	*Federal*	*AAFC*	*Provincial*	*Producer*	*Other*	*Fed+Prov*
Pennock, D. J., & Corre, M. D. (2001). Development and application of landform segmentation procedures. *Soil and Tillage Research*, *58*(3-4), 151-162.	20	16	0	SK	Hepburn	No	No	No	No	Yes	No	No	No
Soon, Y. K., Malhi, S. S., Lemke, R. L., Lupwayi, N. Z., & Grant, C. A. (2011). Effect of polymer-coated urea and tillage on the dynamics of available N and nitrous oxide emission from Gray Luvisols. *Nutrient Cycling in Agroecosystems*, *90*, 267-279.	37	32	0	AB, SK	Beaverlodge, S	Yes	Yes	Yes	Yes	No	No	No	No
Tenuta, M., Mkhabela, M., Tremorin, D., Coppi, L., Phipps, G., Flaten, D., & Ominski, K. (2010). Nitrous oxide and methane emission from a coarse-textured grassland soil receiving hog slurry. *Agriculture, ecosystems & environment*, *138*(1-2), 35-43.	18	0	0	MB	Winnipeg	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Bergstrom, D. W., Tenuta, M., & Beauchamp, E. G. (2001). Nitrous oxide production and flux from soil under sod following application of different nitrogen fertilizers. *Communications in soil science and plant analysis*, *32*(3-4), 553-570.	4	3	0	ON	Guelph	No	Yes	Yes	Yes	No	No	No	No
Drury, C. F., Reynolds, W. D., Tan, C. S., Welacky, T. W., Calder, W., & McLaughlin, N. B. (2006). Emissions of nitrous oxide and carbon dioxide: influence of tillage type and nitrogen placement depth. *Soil Science Society of America Journal*, *70*(2), 570-581.	18	0	0	ON	Harrow	Yes	Yes	Yes	No	No	Yes	No	No
Drury, C. F., Yang, X. M., Reynolds, W. D., & McLaughlin, N. B. (2008). Nitrous oxide and carbon dioxide emissions from monoculture and rotational cropping of corn, soybean and winter wheat. Canadian Journal of Soil Science, 88(2), 163-174.	24	0	0	ON	Harrow	Yes	Yes	Yes	Yes	No	No	No	No

Citation	Data Points			Location		AAFC Affiliation		Funding						
	Total	Inorganic	Organic	Prov	Location / Cluster	Location	Researcher	Federal	AAFC	Provincial	Producer	Other	Fed+Prov
Grant, R. F., & Pattey, E. (2003). Modelling variability in N2O emissions from fertilized agricultural fields. *Soil Biology and Biochemistry*, *35*(2), 225-243.	2	0	0	ON	Ottawa	No	Yes	Yes	No	No	No	No	No
Gregorich, E. G., Rochette, P., St-Georges, P., McKim, U. F., & Chan, C. (2008). Tillage effects on N2O emission from soils under corn and soybeans in Eastern Canada. *Canadian Journal of Soil Science*, *88*(2), 153-16	12	0	0	ON	Ottawa	Yes	Yes	Funding not disclosed					
Kaharabata, S. K., Drury, C. F., Priesack, E., Desjardins, R. L., McKenney, D. J., Tan, C. S., & Reynolds, D. (2003). Comparing measured and Expert-N predicted N 2 O emissions from conventional till and no till corn treatments. *Nutrient Cycling in Agroecosystems*, *66*, 107-118.	4	0	0	ON	Harrow	Yes	Yes	Funding not disclosed					
Lessard, R., Rochette, P., Gregorich, E. G., Pattey, E., & Desjardins, R. L. (1996). *Nitrous oxide fluxes from manure-amended soil under maize* (Vol. 25, No. 6, pp. 1371-1377). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.	7	0	2	ON	Unk	Unk	Yes	Funding not disclosed					
Maggiotto, S. R., Webb, J. A., Wagner-Riddle, C., & Thurtell, G. W. (2000). *Nitrous and nitrogen oxide emissions from turfgrass receiving different forms of nitrogen fertilizer* (Vol. 29, No. 2, pp. 621-630). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.	12	9	0	ON	Guelph	No	No	Yes	No	Yes	No	Yes	Yes
McKenney, D. J., Shuttleworth, K. F., & Findlay, W. I. (1980). Nitrous oxide evolution rates from fertilized soil: effects of applied nitrogen. *Canadian Journal of Soil Science*, *60*(3), 429-438.	8	6	0	ON	Harrow	Yes	Yes	Yes	Yes	No	No	No	No

Citation	Data Points			Location		AAFC Affiliation		Funding						
	Total	*Inorganic*	*Organic*	*Prov*	*Location / Cluster*	*Location*	*Researcher*	*Federal*	*AAFC*	*Provincial*	*Producer*	*Other*	*Fed+Prov*
Tenuta and EG Beauchamp, M. (2003). Nitrous oxide production from granular nitrogen fertilizers applied to a silt loam soil. *Canadian Journal of Soil Science*, *83*(5), 521-532.	5	4	0	ON	Guelph	No	No	Yes	Yes	No	No	No	No
WAGNER-RIDDLE, C., Furon, A., Mclaughlin, N. L., Lee, I., Barbeau, J., Jayasundara, S., ... & Warland, J. O. N. (2007). Intensive measurement of nitrous oxide emissions from a corn–soybean–wheat rotation under two contrasting management systems over 5 years. *Global Change Biology*, *13*(8), 1722-1736.	10	0	0	ON	Guelph	No	No	Yes	Yes	Yes	No	No	Yes
Wagner-Riddle, C., & Thurtell, G. W. (1998). Nitrous oxide emissions from agricultural fields during winter and spring thaw as affected by management practices. *Nutrient Cycling in Agroecosystems*, *52*(2-3), 151-163.	18	0	0	ON	Guelph	No	No	Yes	Yes	Yes	No	No	Yes
Wagner-Riddle, C., Thurtell, G. W., Kidd, G. K., Beauchamp, E. G., & Sweetman, R. (1997). Estimates of nitrous oxide emissions from agricultural fields over 28 months. *Canadian Journal of Soil Science*, *77*(2), 135-144.	9	0	0	ON	Guelph	No	No	Yes	Yes	Yes	No	No	Yes
Drury, C. F., Reynolds, W. D., Yang, X. M., McLaughlin, N. B., Welacky, T. W., Calder, W., & Grant, C. A. (2012). Nitrogen source, application time, and tillage effects on soil nitrous oxide emissions and corn grain yields. *Soil Science Society of America Journal*, *76*(4), 1268-1279.	36	0	0	ON	Harrow	Yes	Yes	Yes	Yes	No	No	No	No
Almaraz, J. J., Mabood, F., Zhou, X., Madramootoo, C., Rochette, P., Ma, B. L., & Smith, D. L. (2009). Carbon dioxide and nitrous oxide fluxes in corn grown under two tillage systems in southwestern Quebec. *Soil Science Society of America Journal*, *73*(1), 113-119.	4	0	0	QC	Montréal	No	Yes	Funding not disclosed					

Citation	Data Points			Location		AAFC Affiliation		Funding						
	Total	*Inorganic*	*Organic*	*Prov*	*Location / Cluster*	*Location*	*Researcher*	*Federal*	*AAFC*	*Provincial*	*Producer*	*Other*	*Fed+Prov*
Chantigny, M. H., Angers, D. A., Rochette, P., Bélanger, G., Massé, D., & Côté, D. (2007). Gaseous nitrogen emissions and forage nitrogen uptake on soils fertilized with raw and treated swine manure. *Journal of environmental quality*, *36*(6), 1864-1872.	46	6	30	QC	Québec City	No	Yes	Yes	Yes	No	Yes	Yes	No
Chantigny, M. H., Pelster, D. E., Perron, M. H., Rochette, P., Angers, D. A., Parent, L. É., ... & Ziadi, N. (2013). Nitrous oxide emissions from clayey soils amended with paper sludges and biosolids of separated pig slurry. *Journal of environmental quality*, *42*(1), 30-39.	18	2	14	QC	Québec City	Yes	Yes	Yes	Yes	No	No	Yes	No
Chantigny, M. H., Rochette, P., Angers, D. A., Bittman, S., Buckley, K., Massé, D., ... & Gasser, M. O. (2010). Soil nitrous oxide emissions following band-incorporation of fertilizer nitrogen and swine manure. *Journal of Environmental Quality*, *39*(5), 1545-1553.	42	36	0	QC	Québec City	Yes	Yes	Yes	Yes	No	No	No	No
Elmi, A., Mehdi, B., Chandra, M., Dam, R., & Smith, D. (2009). Long-term effect of conventional and no-tillage production systems on nitrous oxide fluxes from corn (Zea mays L.) field in Southwestern Quebec. *American Journal of Environmental Sciences*, *5*(3), 238-246.	8	0	0	QC	Montréal	No	No	Yes	Yes	No	No	Np	No
Gagnon, B., Ziadi, N., Rochette, P., Chantigny, M. H., & Angers, D. A. (2011). Fertilizer source influenced nitrous oxide emissions from a clay soil under corn. *Soil Science Society of America Journal*, *75*(2), 595-604	30	27	0	QC	Québec City	Yes	Yes	Yes	No	No	No	No	No
MacDonald, J. D., Rochette, P., Chantigny, M. H., Angers, D. A., Royer, I., & Gasser, M. O. (2011). Ploughing a poorly drained grassland reduced N2O	8	0	0	QC	Québec City	No	Yes	Funding not disclosed					

Citation	Data Points			Location		AAFC Affiliation		Funding					
	Total	*Inorganic*	*Organic*	*Prov*	*Location / Cluster*	*Location*	*Researcher*	*Federal*	*AAFC*	*Provincial*	*Producer*	*Other*	*Fed+Prov*
emissions compared to chemical fallow. Soil and tillage Research, 111(2), 123-132.													
MacKenzie, A. F., Fan, M. X., & Cadrin, F. (1998). Nitrous oxide emission in three years as affected by tillage, corn-soybean-alfalfa rotations, and nitrogen fertilization (Vol. 27, No. 3, pp. 698-703). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.	12	8	0	QC	Montréal	No	No	Yes	No	No	No	No	No
MacKenzie, A. F., Fan, M. X., & Cadrin, F. (1997). Nitrous oxide emission as affected by tillage, corn-soybean-alfalfa rotations and nitrogen fertilization. Canadian Journal of Soil Science, 77(2), 145-152.	35	8	0	QC	Montréal	No	No	Funding not disclosed					
Pattey, E., Blackburn, L. G., Strachan, I. B., Desjardins, R., & Dow, D. (2008). Spring thaw and growing season N2O emissions from a field planted with edible peas and a cover crop. Canadian journal of soil science, 88(2), 241-249.	1	0	0	QC	Montréal	No	Yes	Yes	Yes	No	No	No	No
Pelster, D. E., Chantigny, M. H., Rochette, P., Angers, D. A., Rieux, C., & Vanasse, A. (2012). Nitrous oxide emissions respond differently to mineral and organic nitrogen sources in contrasting soil types. Journal of environmental quality, 41(2), 427-435.	20	4	12	QC	Québec City	No	Yes	Yes	Yes	No	No	No	No
Pelster, D. E., Larouche, F., Rochette, P., Chantigny, M. H., Allaire, S., & Angers, D. A. (2011). Nitrogen fertilization but not soil tillage affects nitrous oxide emissions from a clay loam soil under a maize–soybean rotation. Soil and Tillage Research, 115, 16-26.	12	0	0	QC	Montréal	Yes	Yes	Yes	Yes	No	No	No	No
Rochette, P., Angers, D. A., Bélanger, G., Chantigny, M.	15	0	0	QC	Québec City	Yes	Yes	Yes	No	No	No	No	No

H., Prévost, D., & Lévesque, G. (2004). Emissions of

Citation	Data Points			Location		AAFC Affiliation		Funding						
	Total	Inorganic	Organic	Prov	Location / Cluster	Location	Researcher	Federal	AAFC	Provincial	Producer	Other	Fed+Prov
N2O from alfalfa and soybean crops in eastern Canada. *Soil Science Society of America Journal*, *68*(2), 493-506.													
Rochette, P., Angers, D. A., Chantigny, M. H., & Bertrand, N. (2008). Nitrous oxide emissions respond differently to no-till in a loam and a heavy clay soil. *Soil Science Society of America Journal*, *72*(5), 1363-1369.	12	0	0	QC	Québec City	Yes	Yes	Yes	No	No	No	No	No
Rochette, P., Angers, D. A., Chantigny, M. H., Bertrand, N., & Côté, D. (2004). Carbon dioxide and nitrous oxide emissions following fall and spring applications of pig slurry to an agricultural soil. *Soil Science Society of America Journal*, *68*(4), 1410-1420.	3	0	0	QC	Québec City	Yes	Yes	Yes	Yes	No	No	No	No
Rochette, P., Angers, D. A., Chantigny, M. H., Gagnon, B., & Bertrand, N. (2008). N2O fluxes in soils of contrasting textures fertilized with liquid and solid dairy cattle manures. *Canadian Journal of Soil Science*, *88*(2), 175-187.	12	0	0	QC	Québec City	Yes	Yes	Yes	Yes	No	No	No	No
Rochette, P., van Bochove, E., Prévost, D., Angers, D. A., C o ˆ té, D., & Bertrand, N. (2000). Soil carbon and nitrogen dynamics following application of pig slurry and mineral nitrogen. *Soil Science Society of America Journal*, *64*(4), 1396-1403.	3	0	0	QC	Québec City	Yes	Yes	Yes	Yes	No	No	No	No
Burton, D. L., Zebarth, B. J., Gillam, K. M., & MacLeod, J. A. (2008). Effect of split application of fertilizer nitrogen on N2O emissions from potatoes. *Canadian Journal of Soil Science*, *88*(2), 229-239.	6	4	0	NB	Fredericton	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Zebarth, B. J., Rochette, P., & Burton, D. L. (2008). N2O	9	6	0	NB	Fredericton	Yes	Yes	Yes	Yes	Yes	No	No	Yes

emissions from spring barley production as influenced

Citation	Data Points			Location		AAFC Affiliation		Funding						
	Total	Inorganic	Organic	Prov	Location / Cluster	Location	Researcher	Federal	AAFC	Provincial	Producer	Other	Fed+Prov
by fertilizer nitrogen rate. *Canadian Journal of Soil Science*, *88*(2), 197-205.													
Zebarth, B. J., Rochette, P., Burton, D. L., & Price, M. (2008). Effect of fertilizer nitrogen management on N2O emissions in commercial corn fields. *Canadian Journal of Soil Science*, *88*(2), 189-195	8	0	0	NB	Fredericton	Yes	Yes	Yes	Yes	Yes	No	No	Yes

Note: Adopted from "Soil nitrous oxide emissions from agricultural soils in Canada: Exploring relationships with soil, crop and climatic variables.", by Rochette, P., Liang, C., Pelster, D., Bergeron, O., Lemke, R., Kroebel, R., MacDonald, D., Yan, W., & Flemming, C., 2018, Agriculture, Ecosystems and Environment, 254, 71. Location/Cluster indicate the locations of the field study. Clusters are used to identify groups of studies occurring within the same geographical region. For example, Woodlee and Harrow are group together as Harrow. AAFC research facilities indicates that 1 or more of the field studied was located at an AAFC research facility. AAFC Research was used to identify if 1 or more of the studies authors was affiliated with AAFC at the time of publication. Federal funding includes AAFC and other federal funding sources such as NSER.

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