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ORIGINAL ARTICLE

Developing a country specific method for estimating nitrous oxide emissions from agricultural soils in Canada

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Abstract Accurate estimates of nitrous oxide (N_2O) emissions from agricultural soils and management factors that influence emissions are necessary to capture the impact of mitigation measures and carry out life cycle analyses aimed at identifying best practices to reduce greenhouse gas emissions. We propose improvements to a country specific method for estimating N_2O emissions from agricultural soils in Canada based on a compilation of soil N_2O flux data from recent published literature. We provide a framework for the development of empirical models that could be applied in regions where similar data and information on N_2O emissions are available. The method considers spatial elements such as soil texture, topography and climate based on a quantitative empirical relationship between synthetic N-induced soil N_2O emission factor (EF) and growing season precipitation (P) $\{N_2OEF = e^{(0.00558P-7.7)}\}$. Emission factors vary from less than 0.0025 kg N_2O-N kg N^{-1} in semi-arid regions of Canada to greater than 0.025 kg N_2O-N kg N^{-1} in humid regions. This approach differentiates soil N_2O EFs based on management factors. Specifically, empirical ratio factors are applied for sources of N of 1.0, 0.84, and 0.28 for synthetic N, animal manure N and crop residue N, respectively. Crop type ratio factors where soil N_2O EFs from applied manure- and synthetic-N on perennial crops are approximately 19% of those on annual crops. This proposed approach improves the accuracy of the dominant factors that modulate N_2O emissions from N application to soils.

Keywords Soil N_2O emissions · Synthetic N · Organic N · Crop residue N · Tillage · Perennial/annual crop

Abbreviations

N_2O	Nitrous oxide
EF	Emission factor
NS	Sources of N
ON	Organic N
CRN	Crop residual N
Per	Perennial crops
Ann	Annual crops

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RF Ratio factor
SOC Soil organic carbon

Introduction

In 2016, N_2O emissions from agricultural soils accounted for 75% of the national N_2O emissions in Canada. These emissions have risen by roughly 50% since 1990 (ECCC 2018). Although, N_2O emissions are mainly an outcome of natural microbial denitrification of N in soils, intensive agriculture practices have resulted in significant increases of emissions relative to the natural cycle through the addition of fertilizer to croplands. Agricultural emissions due to synthetic and manure N applications (4.3–5.8 Tg N_2O-N yr^{-1}) and emissions from natural soils (6–7 Tg N_2O-N yr^{-1}) represent 56–70% of all global N_2O sources (Syakila and Kroeze 2011). Direct soil N_2O emissions are calculated and reported to the United Nations Convention on Climate Change by most countries using default emission factors (EFs) (Dechow and Freibauer 2011) defined in the 2006 IPCC Guidelines (IPCC 2006). Direct emissions are estimated as a fraction of soil N inputs, and a default EF of 0.01 kg N_2O-N for every applied kg of N prescribed in the 2006 IPCC Guidelines (IPCC 2006). This value was derived from a global dataset comprising more than 800 N_2O observations (Bouwman et al. 2002a). With the exception of the option of reduced fertilizer inputs, mitigation efforts in agricultural fields would not be captured by either the Tier 1 method, or simple Tier 2 approaches. To effectively account for changes due to the impacts of farm management practices, more complex modelling approaches are required, both in the collection of activity data and in the estimation method.

To address these concerns IPCC (2006) recommends a Tier 2 approach. This involves the development and use of country-specific EFs to improve the accuracy of N_2O emission estimates. The advantages of using country specific EFs are well documented. For instance, when Tier 2 EFs were determined for the United Kingdom, a mean value of 0.0017 ± 0.0002 kg N_2O-N kg^{-1} N was estimated (Buckingham et al. 2014), which is almost 5 times less than the IPCC Tier I value. In Europe, the EFs were largely between 0.0025 and 0.0075 kg N_2O-N kg^{-1} N and the default EF completely failed to correlate with actual emissions (Lesschen et al. 2011). China estimated EFs ranging from 0.0056 to 0.0154 kg N_2O-N kg^{-1} N with a mean of 0.0092 kg N_2O-N kg^{-1} N for upland crops (Shepherd et al. 2015). A recent meta-analysis has suggested that with large variations in application rates there can be a non-linear relationship between EF and N input rates (Shcherbak et al. 2014); however with rates of application in the range of typical application rates in Canada, this has not been observed (Rochette et al. 2018). These efforts clearly illustrate the significance of developing and using country specific EFs and deviating from the default value of 0.01 kg of N_2O-N kg^{-1} N. The IPCC default EF does not account for variations that occur due to types of soil, crop, land use, sources of N and climate.

Some of the key factors that influence the N_2O emissions are; N inputs, land use, soil temperature, water-filled pore space or soil water content, clay, sand, organic C and N content, and precipitation (Butterbach-Bahl et al. 2013; Sozanska et al. 2002; Freibauer and Kaltsmith 2003; Lu et al. 2006). Methodologies to quantify N_2O emissions from agricultural sources are mostly empirical (Bouwman et al. 2002a, b; Dämmgen and Grünhage 2002; Sozanska et al. 2002; Freibauer 2003; Roelandt et al. 2005; Lu et al. 2006; Dechow and Freibauer 2011). All these methods are based on multivariate linear regressions. For instance, a spatial inventory of N_2O emissions from agricultural and non-agricultural soils in Great Britain was proposed using a simple regression model within a GIS framework (Sozanska et al. 2002). The underlying regression model was based on published N_2O data from soils of temperate climates, describing emissions as a function of N input (N), water filled pore space (WFPS), soil temperature (T_S) and land use (A):

$$\begin{aligned} N_2O\left(\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}\right) = {} & -2.7 \\ & + 0.60\,In\,N\left(\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}\right) \\ & + 0.61\,ln\,WFPS\,(\%) \\ & + 0.035T_S\,(^\circ\mathrm{C}) - 0.99A. \end{aligned}$$

In Canada, Rochette et al. (2008) recommended a method using an empirical approach based on data published before 2005. The method was used to quantify direct N_2O emissions from agricultural soils by ecodistrict as the sum of emissions from N inputs as a function of tillage intensity, irrigation, soil texture, landscape position and the practice of summer fallow. Regional EFs were estimated based on experimental results from three regions using linear relationships between soil N_2O emissions and ratios of growing season precipitation (P) to potential evapotranspiration (PE). A more recent publication by Rochette et al. (2018) has expanded the previous effort by extending the spatial and temporal coverage of soil N_2O studies.

The objective of this study was to develop an updated Canadian inventory approach that integrates new Canadian science and measurements by refining key factors that influence N_2O emissions through N transfer and loss in agricultural soils. The framework on which this method is developed provides a useful approach for the development of soil N_2O quantification methodologies in regions with similar climate and soil data and regionally based research of soil management impacts on N_2O emissions.

Method development

Soil N_2O emissions from agricultural soils were estimated by determining EFs of N_2O multiplied by the amount of N from various forms of N sources (NS) such as synthetic N (SN), manure N (ON) and crop residue N (CRN). The methodology described here builds on the implementation of the IPCC Tier 2 method for Canada described in Rochette et al. (2008) and used in the Canadian National Inventory Report (NIR) (ECCC 2018) incorporating additional changes to selected environmental and management factors. Direct sources of N_2O emissions from agricultural soils are differentiated mainly by the NS including SN, ON, urine and dung deposited on pasture, range and paddocks (PRP) by grazing animals, CRN, mineralization of N associated with loss of soil organic matter as well as the cultivation of organic soils. Country specific features of the proposed N_2O EFs for most of the direct emission sources (Rochette et al. 2018) include revisions of EFs based on tillage practices, irrigation and further take into account the impacts of moisture regimes, landscape position and soil texture on rates of N_2O emissions (Fig. 1).

Emission factor (EF) of the spatial unit: ecodistrict (EF_Topo)

The first step in determining the EF is to establish an EF, defined as EF_Topo that principally accounts for the variability in climatic, edaphic and physiographic factors through their impact on soil moisture regimes. The implementation scale of the N_2O model is the Canadian ecodistrict as this represents approximately 405 homogeneous agricultural production regions in Canada. Ecodistricts represent one level within Canada's National Ecological Framework and were characterized by a distinctive assemblage of relief, landforms, geology, soil, vegetation, water bodies and fauna (Ecological Stratification Working Group 1995).

(i) **Climate factor**

Nitrous oxide is mainly produced during denitrification and is therefore greatly influenced by soil oxygen status which is a function of the soil moisture regime. Accordingly, in moisture-limited conditions, N_2O EFs have been shown to increase with increasing rainfall (Dobbie et al. 1999), and thus, climate-variable EFs have been used in estimating regional-scale soil N_2O emissions (Flynn et al. 2005; Rochette et al. 2008). The proposed approach builds on the Canadian method (Rochette et al. 2008) that estimates EFs at the ecodistrict level as a function of the moisture regime, however it uses a combination of either the ratio of the long-term growing season precipitation (P) over potential evapotranspiration (PE) or P.

A compilation of soil N_2O flux measurements since 1990 from published literature (Rochette et al. 2018) identified that P is the most important factor affecting synthetic N-induced N_2O EFs from fertilized agricultural soils in Canada via soil properties and management practices. The relationship can be described as:

$$EF\_CT_i = exp^{(0.00558P_i - 7.7)} \quad (1)$$

where EF_CT_i is moisture-dependent EF (kg N_2O-N kg^{-1} N) and P_i is the annual growing season precipitation in ecodistrict "i" (mm).

(ii) **Topography**

The moisture dependent EF_CT is further modified based on the topography of the ecodistrict to produce the ecodistrict specific EF_Topo. Topography within a

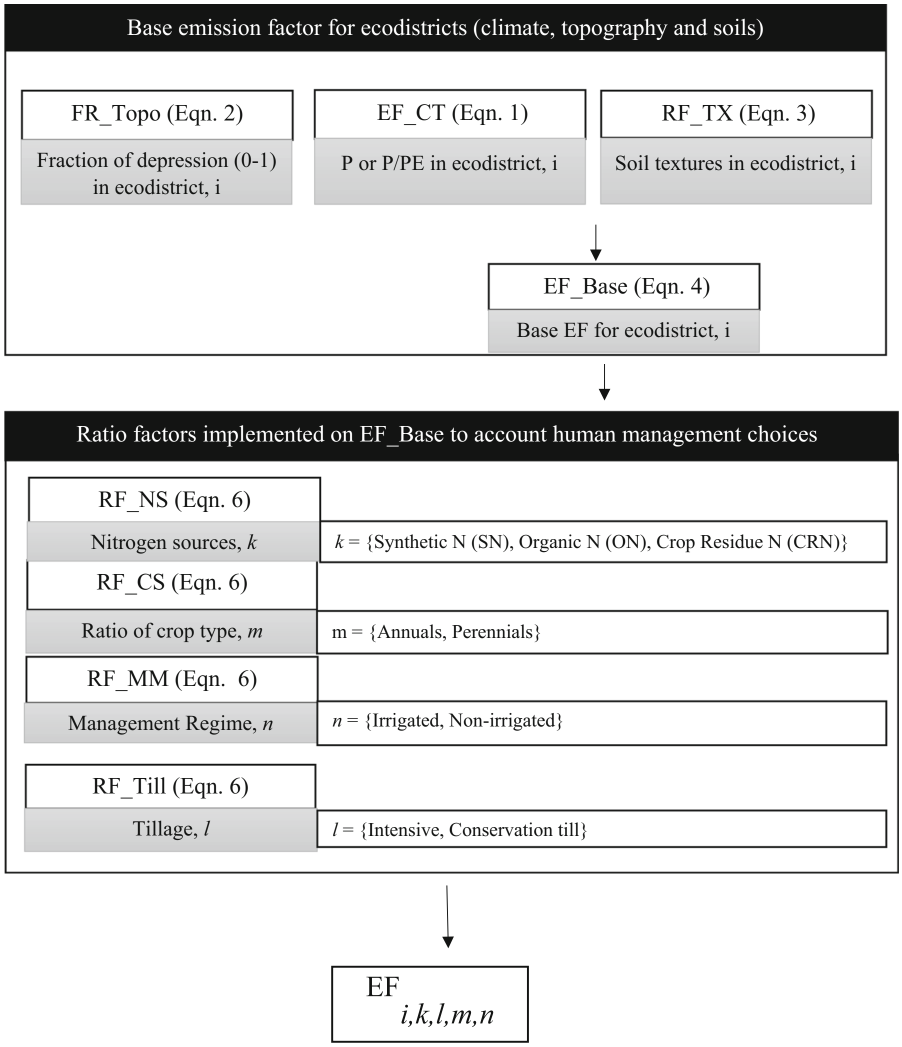

Fig. 1 Schematic diagram on the processes involved in the calculation of base emission factor (EF_Base) and details of ratio factors (RFs) towards the computation of EFs for soil nitrous oxide emissions

landscape affects soil N_2O emissions through its impact on soil moisture, soil texture and soil organic carbon (SOC) (Rochette et al. 2018). The fraction of the landscape occupied by depressions (FR_Topo) or lowland soils occurring in concave portions of the landscape where water accumulates and soils are likely to be saturated for periods of time during the year. Lowland soils within a soil landscape are defined by imperfect drainage and the presence of mottles[1] in the soil profile. Landscape segmentation data were incorporated into the calculation of the national N_2O emission estimates, based on the observations that N_2O emissions are greater in lowland soils occurring in depressions on the landscape, where intermittently saturated soil conditions are favourable to denitrification (Corre et al. 1999; Pennock and Corre 2001; Izaurralde et al. 2004). The fraction of the landscape to which this condition was applied differs among landscape types. MacMillan and Pettapiece (2000) used digital elevation models to characterize the areal extent of upper, mid, lower and depression portions of the landscape and their associated characteristics. These results were used to determine the proportional

[1] Mottles are the product of intermittent oxidation/reduction cycles of iron present in the soil profile. Prevalence, size and colour of mottles are indicative of the soil materials being intermittently saturated for significant periods of time.

distribution of different landforms in the Soil Landscapes of Canada (SLC), which is the basis for determining the proportion of the landscape to which the landscape correction factor (FR_Topo) is applied to calculate the ecodistrict specific N_2O EF.

For humid environments in which P/PE is greater than 1, EF_Topo for landscape depressions are set equal to the EF_CT at actual ecodistrict specific P. For drier regions, where P/PE is less than or equal to 1, the EF_Topo is calculated using actual PE for the lower and depression zone (FR_Topo), and weighed with the non-depression zone using Eq. 2:

$$EF\_Topo_i = \left[\left(EF\_CT_{i,P<PE} \cdot FR\_Topo_i\right) + \left\{EF\_CT_{i,P>PE} \cdot (1 - FR\_Topo_i)\right\}\right] \quad (2)$$

where EF_Topo is a weighted ecodistrict-scale EF that accounts for higher emissions occurring in lowland soils represented by the fraction FR_Topo (kg N_2O-N kg^{-1} N), FR_Topo_i is the fraction of lowland soil in ecodistrict "i", $EF\_CT_{i:P>PE}$ is the moisture-dependent EF based on actual precipitation in ecodistrict "i" (kg N_2O-N kg^{-1} N), $EF\_CT_{i:P<PE}$ is the moisture-dependent EF based on actual PE in ecodistrict "i" (kg N_2O-N kg^{-1} N, applicable to lowland soils).

(iii) **Soil texture**

Within an ecodistrict, the EF_Topo is further influenced by soil texture. Soil texture does not directly influence the N_2O emissions but determines physical and chemical properties that govern the N_2O production and transfer in the soil profile (Arrouays et al. 2006; da Sylva and Kay 1997; Minasny et al. 1999). Therefore, soil texture-related variables are considered to correlate with N_2O emissions from agricultural soils (Hénault et al. 1998; Corre et al. 1999; Chadwick et al. 1999; Bouwman et al. 2002a; Freibauer 2003). Soil texture is not spatially explicit within soil landscapes of Canada polygons (Soil Landscapes of Canada Working Group 2006), but are linked to cropping systems, either annual or perennial crops. Soil texture ratio factors (RFs) for soil N_2O EFs in Eastern Canada have been developed as shown in Table 1, and these individual RFs can be applied to perennial and annual crops.

For each ecodistrict, a weighting factor can be developed that integrates the impact of soil texture on N_2O emissions from agricultural soils based on modifying factors taken from Table 1 and the relative proportion of different textured soils. The weighted modifier is calculated as:

$$RF\_TX_i = \sum_j RF\_TX_j \cdot FR\_TX_{i,j} \quad (3)$$

where RF_TX_i is a weighted modifier which provides a correction of the EF_Topo in ecodistrict "i" based on the soil texture RF_TX_j, "j" is coarse, medium and fine, and $FR\_TX_{i,j}$ is the fraction of different textured soils, in ecodistrict "i". The texture modifier for ecodistrict "i" is applied to the topographic modifier resulting in EF_Base_i

$$EF\_Base_i = EF\_Topo_i \cdot RF\_TX_i \quad (4)$$

Considering the spatially allocated emission modifiers, EF_Base (kg N_2O-N kg^{-1} N) is a function of the three factors that create a base ecodistrict specific value that accounts for the climatic, topographic and edaphic characteristics of the spatial unit for lands.

Source and management based emission factor modifiers

Emissions of N_2O are not only impacted by climatic and soil factors, but sources of N have a significant impact (Arrouays et al. 2006; Bouwman et al. 2002a; Freibauer and Kaltsmith 2003; Maas et al. 2013). Nitrogen source EF modifiers (RF_NS) were also compiled in Table 1 and are applied to the ecodistrict EF already refined by climate, topography and soil texture:

$$EF_{i,k} = EF\_Base_i \cdot RF\_NS_k \quad (5)$$

where $EF_{i,k}$ is the EF considering the impact of the N source on the cropping system and site dependent factors associated with rainfall, topography and soil texture (kg N_2O-N kg^{-1} N) for ecodistrict "i" and N source modifier RF_NS_k.

Rochette et al. (2018) revised the management-based corrections that were developed in their earlier study (Rochette et al. 2008) and added new modifiers. As a result, and consistent with Rochette et al. (2008), the source dependent EF associated with a specific ecodistrict undergoes further modification based on agricultural land management factors such as cropping system, tillage and irrigation.

Table 1 Soil nitrous oxide emission factors (N_2O EF) as influenced by source of nitrogen, soil texture, tillage practice and crop type in Canada

Region	Influencial Factor		Soil N_2O EF kg N_2O-N kg^{-1}N	Ratio factor		References
Canada	Nitrogen Source[a] (RF_NS_k)	Synthetic Nitrogen	0.0211 ± 0.0092	1.00	$RF\_NS_{k=SN}$	Rochette et al. (2018)
		Organic Nitrogen	0.0177 ± 0.0064	0.84	$RF\_NS_{k=ON}$	Rochette et al. (2018)
		Crop Residue Nitrogen	0.0059 ± 0.0027	0.28	$RF\_NS_{k=CRN}$	Charles et al. (2017)
Eastern Canada and the Parcific Maritime ecozone	Soil Texture (RF_TX)	Fine	0.0304 ± 0.0108	2.55	$RF\_TX_{j=F}$	Rochette et al. (2018)
		Medium + Coarse	0.00585 ± 0.0035	0.49	$RF\_TX_{j=MC}$	Rochette et al. (2018)
		Mean	0.0119			
Eastern Canada and the Parcific Maritime ecozone	Tillage Practice (RF_Till)	Conservation Tillage	6.8[b] ± 8.7	1.05	RF_Till	Rochette et al. (2008)
		Conventional Tillage	6.5[b] ± 7.9			Rochette et al. (2008)
Canadian Prairies and the Montane Cordillera ecozone		Conservation Tillage	0.77[b] ± 0.66	0.73	RF_Till	Rochette et al. (2008)
		Conventional Tillage	1.06[b] ± 1.01			Rochette et al. (2008)
Canada	Cropping System (RF_CS)	Annual	0.0211 ± 0.0092	1.00	$RF\_CS_{m=Ann}$	Rochette et al. (2018)
		Perennial	0.0041 ± 0.0013	0.19	$RF\_CS_{m=Per}$	Rochette et al. (2018)

[a]Soil N_2O ratio factor for nitrogen source is only applied on annual crops

[b]Soil N_2O emission factor for tillage practices is expressed as kg N_2O-N ha^{-1}

Emission Factors are refined according to the management regime as:

$$EF_{i,k,l,m,n} = EF\_Base_i \cdot RF\_NS_k \cdot RF\_Till_l \cdot RF\_CS_m \cdot RF\_MM_n \quad (6)$$

where $EF_{i,k,l,m,n}$ is the EF based on N source type "k" in ecodistrict "i" under tillage regime "l", cropping system "m" and moisture management regime "n" (kg N_2O-N kg^{-1} N). The associated ratio factors (RF) are used to adjust EFs based on factors listed in Table 1.

Tillage factors and factors related to moisture management are also spatially dependent. In the case of tillage the impact is regionally based, i.e. difference between Eastern and Western Canada, but soil moisture management factors, specifically irrigation in this case, are calculated for ecodistricts. Though field-scale studies directly investigating N_2O emissions under irrigated and non-irrigated conditions are few and have inconsistent results (Jamali et al. 2015; David et al. 2018) it is well established that irrigation increases denitrification rates (Jambert et al. 1997, Liebig et al. 2005, Hao et al. 2001). Further, it is understood that the objective of irrigation is to match water inputs to potential evapotranspiration to avoid moisture deficits in the soil. Therefore, we adopted the approach recommended by Rochette et al. (2008); (1) irrigation water stimulates N_2O production in a way similar to rainfall, (2) irrigation is applied to eliminate any moisture deficit such that "precipitation plus irrigation water = potential evapotranspiration," and (3) the effect of irrigation on N_2O emissions is in addition to effects of the non-irrigated area within an ecodistrict.

The irrigation modifier is calculated in a similar manner to the topographic correction:

$$RF\_MM_i = \frac{EF\_CT_{i,P=PE}}{EF\_CT_{i,p}} \tag{7}$$

where RF_MM_i is the modifier for moisture management regime in ecodistrict "i" (unitless), $EF\_CT_{i,\,P=PE}$ is the moisture-dependent EF based on equivalency between P and PE in ecodistrict "i" (kg N_2O-N kg^{-1} N), applicable to irrigated soils, and $EF\_CT_{i,P}$, is the moisture-dependent EF in ecodistrict "i" (kg N_2O-N kg^{-1} N).

Distribution of N to the base spatial unit by source

Nitrogen is distributed to agricultural "ecodistricts" based on crop and soil specific recommended application rates (Yang et al. 2011). Organic N is considered the first source of N for crop requirements, while synthetic N is distributed according to remaining crop N requirements and is adjusted using the total provincial N sales taken from Statistics Canada survey results. The amount of animal manure N applied to either annual or perennial crops has an impact on how much synthetic N is used in an ecodistrict. Annual livestock population data from each animal category or subcategory at the provincial level are disaggregated into ecodistricts based on the livestock population distribution reported from the Census of Agriculture. Livestock populations from each category or subcategory are used to estimate the amount of manure N excreted and stored or deposited on PRP by grazing animals, and the amount of manure N applied as fertilizers on agricultural soils. More detailed information on soils, livestock and organic N data sources is included in Table 2.

$$N_{i,k=ON} = \sum_t \left(AAP_{i.t} \cdot N_{EX,t} \cdot AWMS_{i,o} - N\_Loss_{i,t,o}\right) \tag{8}$$

where $N_{i,k=ON}$ is N source, with "k" equal to manure N (ON) spread to fields in ecodistrict "i" (kg N yr^{-1}), $AAP_{i,t}$ is the average number of animals type "t" in ecodistrict "i" (head), $N_{EX,t}$ is the average annual N excreted by animal type "t" (kg N $head^{-1}$ yr^{-1}), $AWMS_{i,o}$ is the fraction of manure treated in animal waste management system "o" in ecodistrict "i" (unitless) and $N\_Loss_{i,t,o}$ is the quantity of manure N lost through volatilization and leaching, for animal type "t" in animal waste management system "o" in ecodistrict "i" (kg N yr^{-1}).

A portion of manure N is not spread, but excreted directly on PRP, therefore not subject to storage:

$$N\_PRP_i = \sum_t AAP_{i,t} \cdot N_{EX,t} \cdot AWMS_{i,t,o=PRP} \tag{9}$$

where N_PRP_i is N excreted directly on PRP in ecodistrict "i" (kg N yr^{-1}), $AAP_{i,t}$ is the average number of animal type "t" in ecodistrict "i" (head), $N_{EX,t}$ is the average annual N excreted by animal type "t" (kg N $head^{-1}$ yr^{-1}), and $AWMS_{i,t,o}$ is the fraction of manure excreted in ecodistrict "i" by animal type "t" based on animal waste management system fraction "o" equal to PRP.

Fertilizer application statistics is a direct function of total fertilizer shipments collected and compiled by a number of agencies in Canada over the past 30 years. From 1990 to 2002, Agriculture and Agri-Food Canada collected annual synthetic N sales data at the provincial level and published Canadian Fertilizer Consumption, Shipments and Trade. From 2003 to 2006, synthetic N data were collected and published by the Canadian Fertilizer Institute. Since 2007, Statistics Canada has collected and published fertilizer sales data annually (Statistics Canada 2018).

Total synthetic fertilizer applied to an individual ecodistrict is then calculated considering the amount of manure N applied to land towards crop requirements and scaled using the provincial N sale values.

Table 2 Data sources for activity and production for estimating nitrous oxide emissions from agricultural soils for Canada

Activities	Time series	Data sources
Animal population		
Cattle	1990–2016	Statistics Canada, Table 32-10-0130-01, number of cattle by class and farm type
Bison, Goats, Horses, Llamas and Alpacas, Deers and Elk, Wild Boars	1990–2016	Statistics Canada (2008). Alternative livestock on Canadian farms: census years 1981, 1986, 1991, 1996, 2001 and 2006 (Cat. No. 23-502-X), 2011 and 2016 Census of Agriculture: Statistics Canada. Table: 32-10-0427-01
Sheep and Lambs	1990–2016	Statistics Canada, Table 32-10-0129-01, number of sheep and lambs on farms
Swine	1990–2006	Statistics Canada, Table 32-10-0290-01, number of hogs on farms at end of quarter, quarterly
	2007–2016	Statistics Canada, Table 32-10-0145-01, hog statistics, number of hogs on farms at end of semi-annual period
Poultry	1990–2006	Selected historical data from the Census of Agriculture, Canada and provinces: census years 1976-2006 (Table 2.16 and Section 4.6 of Statistics Canada (Cat. No. 95-632))
	2007–2016	Statistics Canada, Table 32-10-0428-01, poultry inventory on census day
Crop production		
Field crop production	1990–2016	Statistics Canada, Table 32-10-0359-01, estimated areas, yield, production and average farm price of principal field crops in metric units
Synthetic N fertilizer use	1990–2016	Statistics Canada, Table 32-10-0038-01, fertilizer shipments survey
Soil data/information		
Cultivation of organic Soils	1990–2016	Consultations with regional and provincial soil and crop specialists on areas of cultivated organic soils for annual and perennial crop production (Liang et al. 2004)
Soil C:N ratios	1990–2016	A database containing soil organic carbon and N for all major soils in Saskatchewan (a data set of about 600) was used to derive an average C:N ratio of 11 with a standard deviation of 1.9
Soil Lanscape Polygon of Canada (SLC)		The SLC is a national-scale spatial database describing the types of soils associated with landforms, displayed as polygons at an intended scale of representation of 1:1 million. All SLC polygons are "nested" within the 1995 National Ecological Framework, making it possible to scale up or scale down data and estimates, as required
Losses of soil organic carbon	1990–2016	Activity data on soil organic carbon loss at an ecodistrict level from 1990 to 2016 are transferred from the data reported in the LULUCF Cropland remaining Cropland category to the United Nations Framework Convention on Climate Change (UNFCCC)
Census of Agriculture (CoA) overlaid SLC along with Earch Observations (EO)	1990–2016	A consistent time series of data on crop and animal production and land management practices collected through Census of Agriculture overlaid with SLC, and further adjusted through EO for spatial and temporal distribution of crops, livestock, soils and climate
Toposequence of major Great- or Sub-great Group of Soil Series		Landscape segmentation data are incorporated into the calculation of the national N_2O emission estimates. The fraction of the landscape occupied by lower sections (FR_TOPO) is applied to concave portions of the landscape where soils are likely to be saturated for significant periods of time on a regular basis and where they are imperfectly and poorly drained with mottles

Table 2 continued

Activities	Time series	Data sources
Climate data		
Growing Season Precipitation and Potential Evapotranspiration	1990–2016	There are 958 weather stations in the weather database archived by Agriculture and Agri-Food Canada (AAFC). Long-term normals of growing season potential evapotranspiration (PE, mm), precipitation (P, mm) as well as P/PE from 1981 to 2010 are calculated for all ecodistricts

$$N_{i,k=SN} = \left[\left(\sum_c Rec\_N_{i,c} \cdot A_{i,c}\right) - N_{i,k=ON}\right] \cdot \frac{S_p}{\sum_{i=p,c} Rec\_N_{i,c} \cdot A_{i,c}} \quad (10)$$

where $N_{i,k=SN}$ is the total amount of synthetic N applied in ecodistrict "i" (kg N yr^{-1}), $Rec\_N_{i,c}$ is the recommended N rate for crop type "c" in ecodistrict "i" (kg N ha^{-1}), $A_{i,c}$ is the area of crop type "c" in ecodistrict "i" (ha), $N_{i,k=ON}$ is manure N (kg N yr^{-1}) that is available for crop application in ecodistrict "i" (see Eq. 8), and S_p is synthetic N fertilizer sales in province "p" (kg N yr^{-1}). The distribution of N requires the disaggregation of the cropping systems "m" (annual and perennial) to individual crop type "c".

Manure and synthetic fertilizer are not spread on crops equally; certain crops tend to receive greater quantities of manure N (Sheppard et al. 2010), and therefore manure N is applied preferentially within each ecodistrict to those crops.

The total quantity of N in crop residue is calculated at the ecodistrict scale, per crop type. Statistics Canada collects and publishes annual field crop production data by province (Statistics Canada 2018, Table 32-10-0359-01). The area seeded and the yield of each crop are reported at the census agricultural region and provincial levels, and yields have been allocated to Soil Landscapes of Canada (SLC) polygons through area overlays by Agriculture and Agri-Food Canada. Specific parameters for each field crop are listed in Table 3 and crop residue N is calculated as:

$$N_{i,k=CRN} = \sum_c PN_{i,c} \cdot FR\_RNW_{i,c} \cdot [R\_AG_c \cdot (1-(FR\_Burn_c + FR\_Bale_c)) \cdot N\_AG_c + (R\_BG_c \cdot N\_BG_c)] \quad (11)$$

where $N_{i,k=CRN}$ is total amount of crop residue N that is returned to soils for ecodistrict "i", excluding N losses due to residue burning, and baling (kg N yr^{-1}), $PN_{i,c}$ is total production of crop type "c" that is renewed annually in ecodistrict "i" (kg DM yr^{-1}) (see Eq. 12), $FR\_RNW_{i,c}$ is the fraction of total area of perennial crops renewed annually, R_AG_c is ratio of above-ground residues to harvested yield [kg dry matter (DM) kg^{-1}], FR_Burn_c is the fraction of total area burned annually for crop type "c", FR_Bale_c is the fraction of total area that is baled annually for crop type "c", N_AG_c is N content of above-ground residues for crop type "c" (kg N kg^{-1} DM), R_BG_c is ratio of below-ground residues to harvested yield for crop type "c", and N_BG_c is the N content of below-ground residues for crop type "c" (kg N kg^{-1} DM).

Based on available literature we propose to use the dry matter partition of Thiagarajan et al. (2018), supplemented by Janzen et al. (2003) as listed in Table 3. Crop production data are available only by province and need to be reconciled with the estimates based on crop area multiplied by average yield for each crop type at the ecodistrict level, and aggregated to the provincial level as shown in Eq. 12. Total annual crop production is calculated according to national yield statistics collected by Statistics Canada:

$$PN_{i,c} = \frac{A_{i,c} \cdot Y_{i,c}}{\sum_i (A_{i,c} \cdot Y_{i,c})} \cdot PN_{c,p} \cdot (1 - MC_c) \quad (12)$$

where $PN_{i,c}$ is total production for crop type "c" that is renewed annually in ecodistrict "i" (kg DM yr^{-1}), $A_{i,c}$ is area under crop type "c" in ecodistrict "i" (ha), $Y_{i,c}$ is average yield for crop "c" in ecodistrict "i" (kg ha^{-1} yr^{-1}), $PN_{c,p}$ is total crop production for crop type "c" in province "p" (kg DM yr^{-1}), and MC_c is the water content of crop product for crop type "c" (fraction).

Table 3 Dry matter partition and nitrogen concentration of major field crops among grain yield, above-ground shoot, and roots in Canada

Crop	Moisture Content of Product[a] (H_2O %)	Linear Regression Coefficient[b]		Crop Yield[c] (Mg ha^{-1})	Roots (% of DM)	Yield (% of DM)	Above-ground residue (% of DM)	Yield range[c] (Mg ha^{-1})	Concentration of N in crop components			References
		Intercept	Slope						Yield (g N kg^{-1})	Above-ground Residue (g N kg^{-1})	Roots (g N kg^{-1})	
Wheat	12	0.015	0.344	4	19	35	46	1–8	25.6	6.6	10.5	Thiagaragan et al. (2018)
Maize	15	0.015	0.369	10	20	37	43	3–20	12.7	9.4	7.6	Thiagaragan et al. (2018)
Oat	12	0.029	0.357	4	30	36	34	2–6	24.3	6.8	13.8	Thiagaragan et al. (2018)
Barley	12	0.028	0.373	4	17	38	45	1–6	20.8	8.8	12.4	Thiagaragan et al. (2018)
Dry Pea	13	0.071	0.163	4	18	18	64	0.5–4	37.4	21.0	22.0	Thiagaragan et al. (2018)
Chickpea	13	0.063	0.301	4	18	32	50	1–5	47.2	23.7	15.0	Thiagaragan et al. (2018)
Lentil	13	0.059	0.305	2	19	33	48	0.2–3	38.9	11.7	10[d]	Thiagaragan et al. (2018)
Soybean	14	0.099	0.2	4	18	22	60	1.5–4	62.5	6.6	10[d]	Thiagaragan et al. (2018)
Canola	9	0.046	0.18	4	27	19	54	0.5–4.5	38.2	12.5	8.8	Thiagaragan et al. (2018)
Flax	8	0.11	0.171	2	16	23	61	0.2–2.5	39.9	12.2	10[d]	Thiagaragan et al. (2018)
Potato	75	0	0.795	8	9	80	12	5–13	12.4	13.0	28.6	Thiagaragan et al. (2018)

Table 3 continued

Crop	Moisture Content of Product[a] (H_2O %)	Linear Regression Coefficient[b]		Crop Yield[c] (Mg ha^{-1})	Roots (% of DM)	Yield (% of DM)	Above-ground residue (% of DM)	Yield range[c] (Mg ha^{-1})	Concentration of N in crop components			References
		Intercept	Slope						Yield (g N kg^{-1})	Above-ground Residue (g N kg^{-1})	Roots (g N kg^{-1})	
Rye	12				15	34	51		18	6	10	Janzen et al. (2003)
Mixed Grains	12				20	33	47		22.3	6.3	10	Janzen et al. (2003)
Buckwheat	12				20	24	56		18	6	10	Janzen et al. (2003)
Field Dry Beans	13				20	46	34		37	18	10	Janzen et al. (2003)
Mustard	9				15	26	60		40	8	10	Janzen et al. (2003)
Sunflower	2				20	27	53		24	10	10	Janzen et al. (2003)
Silage Corn	70				20	72	8		13	13	7	Janzen et al. (2003)
Canary	12				20	20	60		25	7	10	Janzen et al. (2003)
Safflower	2				20	27	53		24	10	10	Janzen et al. (2003)
Tobacco	20				20	64	16		20	10	10	Janzen et al. (2003)
Sugar Beets	80				5	76	19		10	29	10	Janzen et al. (2003)
Triticale	12				20	32	48		22	6	10	Janzen et al. (2003)

[a]Janzen et al. (2003)

[b]Fan et al. (2017)

[c]Dry matter partition is calculated based on a fixed crop yield

Calculations of direct sources of soil N_2O emissions: alignment with the 2006 IPCC Guidelines

The direct sources of N_2O emissions identified in the 2006 IPCC Guidelines include: N_2O from synthetic fertilizer application (N_2O_{SN}), organic nitrogen application (N_2O_{ON}), crop residue (N_2O_{CRN}), decomposition of native soil organic C (N_2O_{SOC}), cultivation of organic soil (N_2O_{OS}) and pasture, range and paddock (N_2O_{PRP}).

Emissions from each N source are calculated according to the site, source and management specific EFs and N fractions that apply to those sources. For example, synthetic N fertilizer emissions are the sum of emissions from the application of synthetic N on annual and perennial crops in all ecodistricts across Canada, considering the ecodistrict specific climate, soil and topography.

$$N_2O_{k=SN,ON,CRN} = \sum_{k=SN,ON,CRN}^{i}\left[\sum_{m=Ann}(EF_{i,k}\cdot N_{i,k}) + \sum_{m=Per}(EF_{i,k}\cdot N_{i,k})\right]\cdot 44/28 \quad (13)$$

The application of synthetic N fertilizers, organic N and crop residues are all calculated according to the same approach. $N_2O_{k=SN,ON,CRN}$ is the soil N_2O emissions from synthetic fertilizer, manure and crop residue, $EF_{i,k}$ is the emission factor for N source "k" in ecodistrict "i", $N_{i,k}$ is the quantity of nitrogen applied from N source "k" in ecodistrict "i".

The other IPCC source categories are treated individually. In the case of N loss resulting from the decomposition of native SOC, the emissions are calculated as:

$$N_2O_{k=SOC} = \sum_{i} EF_{i,k=CRN,m=Ann}\cdot C_{i,k=SOC}\cdot 1/R\cdot 44/28 \quad (14)$$

where N_2O_{SOC} is the soil N_2O emissions resulting from losses of SOC, and in turn N because of changes in cropland management practices (kg N_2O-N yr^{-1}), C_{SOC} is the amount of SOC losses in ecodistrict"i" (kg C yr^{-1}), and R is the C/N ratio of SOC.

The emission factor applied to N loss associated with native SOC loss is the same as the EF for crop residue. Nitrogen mineralized during SOC loss is estimated through the ecodistrict specific C loss estimates based on the method outlined in McConkey et al. (2007) and a C:N ratio of 11 with a standard deviation of 1.9 derived from data for major soils in Saskatchewan (largest area of agricultural land in Canada). Manure N deposited on PRP is calculated based on the N fraction derived using Eq. 9 (N_{PRP}). Emission factors from studies by Rochette et al. (2014) for Eastern Canada and Lemke et al. (2012) for Western Canada were used and reported in the National Inventory Report of Canada (ECCC 2018).

The IPCC Tier 1 method is used to estimate N_2O emissions from cultivated organic soils. The IPCC default EFs from cultivation of organic soils for boreal and temperate region are 13 kg N_2O-N ha^{-1} yr^{-1} for annual crop, and 4.3 kg N_2O-N ha^{-1} yr^{-1} for perennial crop, respectively (IPCC 2014).

Canada reports two country specific sources of soil N_2O emissions. The presence of irrigation, whereas emissions from N applied to annual crops are additionally modified by the type of tillage that is used in annual crop production for the specific ecodistrict as follows:

$$N_2O\_MM_i = \left[\sum_{m=Ann,k=SN,ON,CRN}^{i}(N_{i,k}\cdot EF_{i,k}) + \sum_{m=Per,k=SN,ON}^{i}(N_{i,k}\cdot EF_{i,k})\right]\cdot FR\_MM_i\cdot(RF\_MM_i - 1)\cdot\frac{44}{28} \quad (15)$$

where $N_2O\_MM_i$ is the net emissions in ecodistrict "i" that are subject to irrigation on both annual and perennial crops (kg N_2O yr^{-1}), and FR_MM_i and RF_MM_i are the fraction of irrigation (fraction) and irrigation RF (unitless) in ecodistrict "i", respectively.

$$N_2O\_Till_i = \sum_{m=Ann,k=SN,ON,CRN}^{i}(N_{i,k}\cdot EF_{i,k})\cdot(RF\_Till_i - 1)\cdot FR\_Till_i\cdot 44/28 \quad (16)$$

where $N_2O\_Till_i$ is the net emissions/removals in ecodistrict "i" that are subject to conservation tillage on annual crops (kg N_2O yr^{-1}), and FR_Till_i and RF_Till_i are the fraction of conservation tillage (fraction) and the tillage RF (unitless) in ecodistrict "i", respectively.

Calculations of indirect sources of N_2O emissions: alignment with the 2006 IPCC Guidelines

Indirect sources of N_2O emissions include volatilization and redeposition of synthetic and manure N, and leaching and runoff of N (Eqs. 17 and 18) using the 2006 IPCC default EFs (EF_4 in Eq. 17 and EF_5 in Eq. 18). A country-specific method was used to estimate ammonia emissions from synthetic N application. The method closely follows the approach of Sheppard et al. (2010a), who applied the regression model developed by Bouwman et al. (2002a) to derive regionally specific NH_3 EFs for Canada and applies the same basic principles as the N_2O model, considering climate, crop type, soil and management factors. Ammonia EFs are based on the type of synthetic N fertilizers, degree of incorporation into soil, crop type differing for annual and perennial crops and soil chemical properties. A country-specific method is also used to estimate ammonia emissions from dairy and swine manure applied to agricultural soils. The regionally specific ammonia loss factors from Sheppard et al. (2010b) and Sheppard et al. (2011) expressed as fractions of total ammoniacal N (TAN), were converted to fractions of total N based on the approach described in Chai et al. (2016). These factors consider the losses and transformation of the manure N that occur during the storage of manure as well as field application methods, for each animal type and ecoregion. Weighted loss factors for all dairy cattle and swine were inserted into Eq. 17 as FR_GasM by ecodistrict. For all other livestock, a fixed FR_GasM of 0.2 was used (IPCC 2006).

$$N_2O\_ATD = \sum_i \left[\left(N_{i,m,k=SN} \cdot FR\_GasF_{i,m} \right) + \left(N_{i,t,k=ON} \cdot FR\_GasM_{i,t} \right) + \left(N_{i,t,k=PRP} \cdot FR\_GasPRP_{i,t} \right) \right] \cdot EF_4 \cdot 44/28 \quad (17)$$

where N_2O_ATD is the amount of N_2O emissions due to volatilization and re-deposition of ammonia (kg N_2O-N yr^{-1}), $N_{i,m,k=SN}$ is the amount of SN applied in ecodistrict "i" by cropping system "m" (kg N yr^{-1}), $FR\_GasF_{i,m}$ is the fraction of SN that volatilizes as NH_3-N in ecodistrict "i" under cropping system "m", $N_{i,t,k=ON}$ is the amount of ON applied in ecodistrict "i" for animal type "t" (kg N yr^{-1}), $FR\_GasM_{i,t}$ is the fraction of ON that volatilizes as NH_3-N in ecodistrict "i" for animal type "t" (fraction), $N_{PRP\ i,t,k=PRP}$ is the amount of manure N deposited on PRP in ecodistrict "i" for animal type "t" (kg N yr^{-1}); $FR\_GasPRP_{i,t}$ is the fraction of PRP volatilized as NH_3-N in ecodistrict "i" for animal type "t" (0.2 kg NH_3-N kg^{-1} N, IPCC 2006), and EF_4 is the default volatilization and re-deposition EF from the 2006 IPCC Guidelines (0.01 kg N_2O-N kg^{-1} N).

$$N_2O\_Leach = \sum_i \left[N_{i,k} \right] \cdot FR\_Leach_i \cdot EF_5 \cdot 44/28 \quad (18)$$

where N_2O_Leach is the amount of N_2O emissions due to leaching and runoff N (kg N_2O-N yr^{-1}), $N_{i,k}$ is the amount of N from SN, ON, CRN, and PRP in ecodistrict "i" (kg N yr^{-1}), FR_Leach_i is the fraction of N subject to leaching or runoff in ecodistrict "i" and EF_5 is the default leaching and runoff EF from the 2006 IPCC Guidelines (0.0075 kg N_2O-N kg^{-1} N).

The amount of leached N (FR_Leach, fraction) can be as low as 0.05 in regions where P is much lower than PE, such as in the Prairie region of Canada, or as high as 0.3 in humid regions (IPCC 2006) of Eastern Canada. It was assumed that FR_Leach would vary from 0.05 to 0.3, depending on the ecodistrict using Eq. 19 (Rochette et al. 2008).

$$FR\_Leach_i = 0.3247 \cdot \frac{P_i}{PE_i} - 0.0247 \quad (19)$$

Two examples of calculations including weather information, RFs, EFs, and quantities of N from various sources; one ecodistrict for Western Canada and the other for Eastern Canada, are provided for references, and emission estimates attached in Appendix A.

Results

In this study, several improvements for estimating soil N_2O emissions from agricultural soils in Canada in light of more recent studies are noteworthy; (1) improved quantitative relationship between the growing season precipitation and synthetic N-induced soil N_2O EF, (2) soil N_2O RFs accounting for differences in emissions based on the source of N input, (3) refined N_2O RFs for accounting difference in soil texture, and (4) established soil N_2O RF for differentiating the impact of cropping system on soil N_2O emissions. The method further eliminates the upper limit of N-induced EFs, using the PE for estimating soil N_2O emissions for the lower and depression zone of an ecodistrict and irrigation when P < PE.

Revisions in EF_Topo

The Canadian emissions model established by Rochette et al. (2008) used an upper limit of N-induced soil N_2O EF ($EF\_Topo_{,P=PE}$ = 0.0172 kg N_2O-N kg^{-1} N) when P/PE is equal to 1 or greater, and this value was applied nationwide for the lowland soils and depressions. This value represented a maximum emission under humid soil conditions. In this new method, with the introduction of a precipitation based EF calculation, it was possible to calculate an EF that is regionally specific and based on local climate. In the revised method: (1) when P is less than PE the upper limit of N-induced soil N_2O EF depends on PE; and (2) when P is equal or greater than PE the N-induced soil N_2O EF depends on P and EFs are not corrected for topography. Overall, synthetic N-induced soil N_2O EFs for lowland soils and depressions vary among ecodistricts from 0.007 to 0.024 kg N_2O-N kg^{-1} N with a mean of 0.012 kg N_2O-N kg^{-1} N. On a provincial basis, maximum N-induced soil N_2O EFs vary from as low as 0.01 kg N_2O-N kg^{-1} N for British Columbia to as high as 0.016 kg N_2O-N kg^{-1} N for Newfoundland and Labrador (Fig. 2).

Among all ecodistricts long-term average of P varies from 195 mm to 708 mm whereas long-term average of PE varies from 480 mm to 690 mm. The N-induced soil N_2O EFs are generally lower with the proposed method when P is less than 650 mm while the opposite is true when P is greater than 650 mm.

After adjustments for lowlands and depressions, a weighted average of synthetic N-induced soil N_2O EF (EF_Topo) for each ecodistrict was calculated using Eq. 2. On an ecodistrict basis, with the proposed method, EF_Topo varies from 0.002 kg N_2O-N kg^{-1} N to 0.024 kg N_2O-N kg^{-1} N, in contrast with the EF_Topo that varied from 0.003 kg N_2O-N kg^{-1} N to 0.017 kg N_2O-N kg^{-1} N using the previous method (Fig. 3). There are important differences in EF_Topo between the proposed and the previous method for each province (Fig. 4). The overall national average of synthetic N-induced EF_Topo along with its standard deviation from all ecodistricts is 0.006 (± 0.003) kg N_2O-N kg^{-1} N for the proposed method vs 0.01

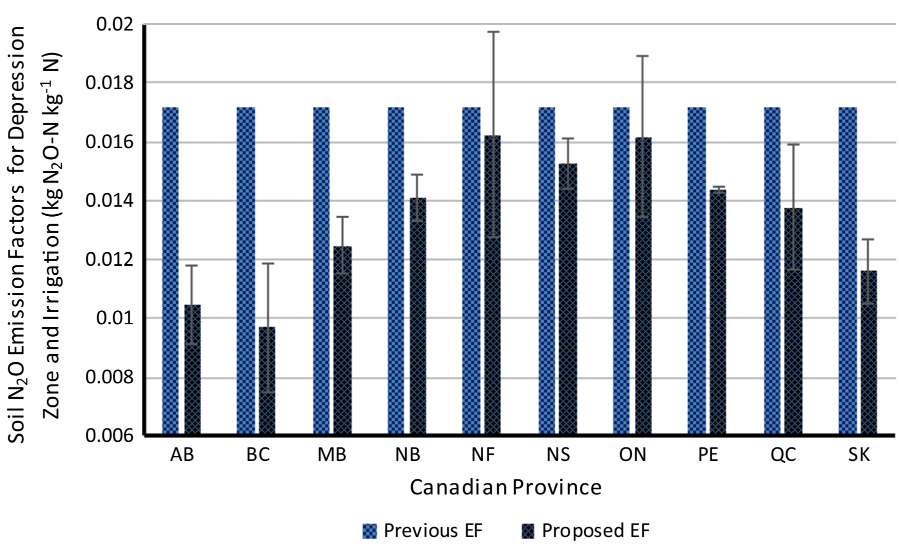

Fig. 2 Average maximal N-induced soil nitrous oxide emission factors for low landscape position of ecodistricts and irrigation derived previously through a linear function of growing season precipitation over potential evapotranspiration and an exponential equation with the growing season precipitation for each province of Canada (AB: Alberta; BC: British Columbia; MB: Manitoba; NB: New Brunswick; NF: Newfoundland and Labrador; NS: Nova Scotia; ON: Ontario; PE: Prince Edward Island; QC: Quebec; SK: Saskatchewan)

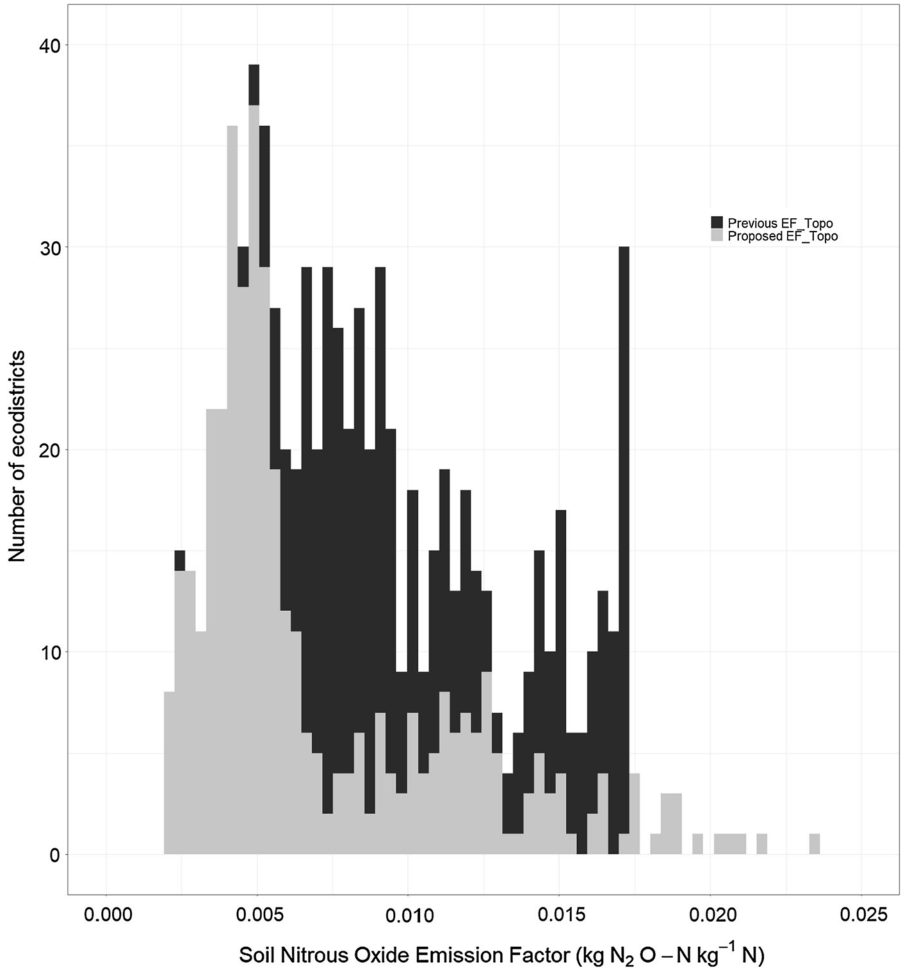

Fig. 3 Distribution of synthetic N-induced soil nitrous oxide emission factors (EF_Topo) adjusted for low landscape position of ecodistricts derived previously through a linear function of growing season precipitation over potential evapotranspiration and an exponential equation with the growing season precipitation for each province of Canada

(± 0.003) kg N_2O-N kg^{-1} N for the previous method, respectively.

Treatment of soil texture and cropping systems

Rochette et al. (2008) proposed soil N_2O texture RF_Till of 1.0 in Western Canada, and 0.8 for coarse and medium textured soils, and 1.2 for fined textured soils in Eastern Canada. With the expansion of the dataset Rochette et al. (2018) found no difference in the effect of soil texture on soil N_2O emissions on the Canadian prairies, but significant changes in soil N_2O RF_Till (RF_TX_{CM} = 0.49 for coarse and medium textured soils, and RF_TX_F = 2.55 for the fine-textured soil) in Eastern Canada. Consequently, the RF_Till values are revised for each province (Table 4).

Annual crops show an N_2O EF value significantly greater than that of the perennial crops for both synthetic- and organic-N in Eastern Canada (Rochette et al. 2018). The N_2O EF estimate for the perennial crops are approximately 5 times lower ($RF\_CS_{M=Per-}$ = 0.19, Table 1). Values of N_2O EF for soils receiving organic N (0.0208 kg N_2O-N kg^{-1} N) are 22% lower than synthetic N (0.0267 kg N_2O-N kg^{-1} N) under annual crop production, whereas there was no difference in the N_2O EF between organic- and

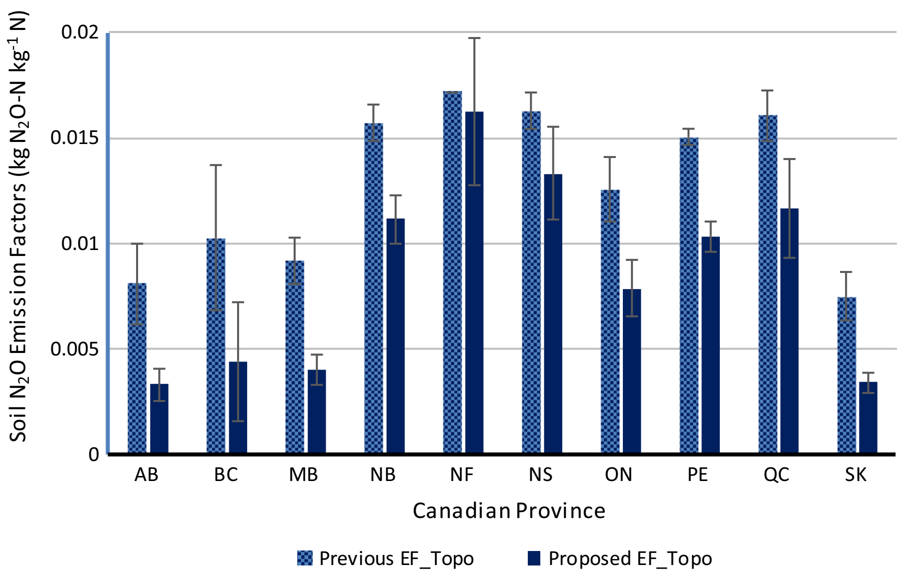

Fig. 4 Average synthetic N-induced soil nitrous oxide emission factors (EF_Topo) adjusted for low landscape position of ecodistricts derived previously through a linear function of growing season precipitation over potential evapotranspiration and an exponential equation with the growing season precipitation for each province of Canada (AB: Alberta; BC: British Columbia; MB: Manitoba; NB: New Brunswick; NF: Newfoundland and Labrador; NS: Nova Scotia; ON: Ontario; PE: Prince Edward Island; QC: Quebec; SK: Saskatchewan)

Table 4 Comparision of soil texture ratio factors for soil nitrous oxide emissions between the proposed method and the method used by Rochette et al. (2008) by province for Canada

Province	Annual crop		Perennial crop	
	Previous method	Proposed method	Previous method	Proposed method
Fraction				
Alberta	1.00	1.00	1.00	1.00
British Columbia	1.00	0.92	1.00	0.92
Manitoba	1.00	1.00	1.00	1.00
New Brunswick	0.80	0.51	0.80	0.51
Newfoundland and Labrador	0.73	0.45	0.80	0.49
Nova Scotia	0.80	0.49	0.80	0.49
Ontario	0.89	0.94	0.87	0.92
Prince Edwards Island	0.80	0.49	0.80	0.49
Quebec	0.86	0.81	0.86	0.78
Saskatchewan	1.00	1.00	1.00	1.00

synthetic-N fertilizers under perennial crop production (Table 1).

Source specific emission factors

Rochette et al. (2018) compared soil N_2O EFs between SN and ON in Ontario and Quebec and reported average soil N_2O EFs of 0.0211 (± 0.0092) kg N_2O-N kg^{-1} N for SN, and 0.0177 (± 0.0064) kg N_2O-N kg^{-1} N for ON, respectively (Table 1). Based on these findings, RF_NS_{ON} is determined as 0.84. Charles et al. (2017) reported similar results of 0.0082 kg N_2O-N kg^{-1} N for ON sources and 0.0134 kg N_2O-N kg^{-1} N for SN using global estimates of N_2O EFs.

The factors developed from recent literature for correcting EFs for tillage remain relatively unchanged. However, for the practice of summer fallow, a farming practice typically used on the Canadian prairies to conserve soil moisture, significant changes have been proposed. Factors that stimulate N_2O emissions under summer fallow relative to continuous cropping include higher soil water content, temperature and available C and N. Rochette et al. (2008) developed a method for estimating soil N_2O emissions as a result of summer fallow based on field observations that there were no differences in soil N_2O emissions between the fertilized and the summer fallow plots. Without any external N input in the summer fallow, soil N_2O emissions would have to result from soil N mineralization and interactions among summer fallow, soil physical and chemical properties.

Rochette et al. (2008) estimated ammonia emissions from manure N excretion and storage and land application as well as synthetic N application using the IPCC default EFs. In the proposed method, ammonia emissions from synthetic N application are estimated using an empirical model by incorporating type of N fertilizers, method of N application, crop type, climate and soil chemical properties (Bouwman et al. 2002a; Sheppard et al. 2010a). Country specific methods are also used for estimating ammonia emissions during manure storage, land application as well as manure N deposited on PRP by grazing animals. The fraction of SN lost through volatilisation varies from 1.5% to 20% depending on the region, the N source and the application method relative to the IPCC default of 10%, which does not take into account Canadian climate and management practices.

Discussion

Revisions in EF_Topo

The information compiled in Rochette et al. (2018) provided the means to develop a more robust approach than previously available to the treatment of climatic, edaphic and topographic corrections to EFs. Variations in emissions of N_2O from the addition of N to agricultural soils in Canada can be estimated by taking into account a few variables. The mean EF for the region is determined as the weighted average of the different factors that influence N_2O emissions for that specific area based on their relative occurrence on the landscape. In Canada data from weather stations, Soil Landscape of Canada and the Census of Agriculture in combination with annual Statistics Canada surveys provide a network of data that can be used with such an approach.

Though the derivation of N-induced soil N_2O EFs for the lowland soils and depressions and irrigation of an ecodistrict is conceptual, as in Rochette et al. (2008), the effect of soil moisture on soil N_2O is considered to be more realistic as it relates EFs back to the local hydrology and climate. This is true, in particularly, in the case of irrigation as rates are likely based on PE where agricultural managers may equilibrate moisture deficits by irrigation. For lowland soils, the PE is more likely to act as a better proxy for soil microbial activity that could impact emission rates than simply establishing single maximum emission rate nationally.

The elimination of the upper limit on synthetic N-induced soil N_2O EF, when P is greater than PE, is a result of recent findings by Rochette et al. (2018). With an expansion of the dataset, a similar quantitative linear relationship between N-induced soil N_2O EF and the ratio of P over PE was established similar to Rochette et al. (2008), with a better statistical fit (R^2 = 0.44**). An exponential relationship between P and synthetic N-induced soil N_2O EF also yielded an improved statistical fit (R^2 = 0.53**) resulting from a better representation of emissions occurring in the middle of the x-axis representing regions between the semi-arid and semi-humid environments in Canada (Fig. 3). Emissions tended to trend strongly upward in wetter environments. For the proposed method, the overall average synthetic N-induced soil N_2O EF along with its standard deviation among all ecodistricts was 0.0052 (± 0.0034) kg N_2O-N kg^{-1} N, and it contrasts with a mean of 0.0097 kg N_2O-N kg^{-1} N and a standard deviation of ± 0.0035 kg N_2O-N kg^{-1}N for the previous method (Fig. 3).

The quantitative estimates with the updated dataset represent an improvement in terms of defining local EFs for synthetic N fertilizer inputs compared to either national or regional mean estimates as they account for spatial variations in the key controlling variables. It is worth noting that the 126 observations used in Rochette et al. (2018) to estimate an EF for the Prairies region was a much more complete dataset than the 48 observations from Rochette et al. (2008). The

Prairie region estimates in Rochette et al. (2008) were obtained from poorly fitted regressions of N_2O emissions versus synthetic N rate ($R^2 < 0.06$) rather than from individual EFs as in Rochette et al. (2018). The non-linear relationship between P and EFs have been observed by Lu et al. (2006) who reported a similar relationship between annual precipitation and soil N_2O EF in China. Emission factors increase non-linearly with precipitation and this relationship highlights the important role of soil moisture status on N_2O emissions.

At this time, not all factors that affect N_2O emissions are integrated into the current methodology as there are not always definitive evidence in the literature related to the implementation of specific management based mitigation actions. It has been proposed that advanced fertilizer management related to the timing of application, the type of fertilizer in combination with the rate of application and fertilizer placement will impact emissions (Woodley et al. 2018; Drury et al. 2017; Abalos et al. 2016a, b). Other factors such as agricultural drainage may further influence emissions at the landscape scale. While not currently implemented in the methodology due to lack of EFs and activity data at the national scale, such additional factors could be easily integrated into this framework through the use of additional EF modifiers under the existing categories.

Treatment of soil texture and cropping systems

Soil texture modifies N_2O emissions through its impact on soil moisture, soil porosity, SOC content and oxygen availability (da Sylva and Kay 1997; Minasny et al. 1999; Arrouays et al. 2006). There is no RF_TX for the interior portion of British Columbia (Mountane Cordillera Reporting Zone) because climate and soils in this region resembles more the Canadian prairies. The RF_TX is applied for the Pacific Maritime Reporting Zone of British Columbia due to its similarity with the more humid region of Eastern Canada.

Less soil disturbance, longer growing season and a more efficient use of available N by plants in perennial than annual cropping systems can result in differences in soil N_2O emissions. Maas et al. (2013) reported that annual crops emitted more than four times the N_2O than the perennial forage stand in Manitoba. This interactive effect of fertilizer N regime with crop type on the N_2O EF may have been a result of slower release of mineral N from organic N fertilizers under annual crops whereas increasing competition for available NO_3^- and reducing soil water and thereby decreasing the degree of anaerobiosis in the soils may play more important role in controlling N_2O emissions under perennial crops, regardless of fertilizer N type.

Source specific emission factors

A major improvement of the proposed method over the previous method developed by Rochette et al. (2008) is a ratio factor that accounts for the difference in N sources, namely ON versus SN and crop residue/soil mineralizable N versus SN. Differences in N dynamics after the application of N containing products can result in differing rates of emissions. The N in manure is partially in the form of organic N which can take time to be mineralized and as a consequence be converted and emitted as N_2O.

Crop residue N_2O emissions in Canada account for roughly one-third of total direct emissions based on the use of equivalent EF in Rochette et al. (2008). A global literature review (Charles et al. 2017) on N_2O EFs from agricultural soils after addition of organic amendments through a meta-analysis demonstrated three groups of organic amendments with similar EFs; the high risk group including animal slurries, waste waters and biosolids (1.21 ± 0.13%), the medium-risk group including solid manure, composts with fertilizers, and crop residues with fertilizers (0.35 ± 0.13%), and the low-risk group including composts, crop residues, paper mill sludge and pellets (0.02 ± 0.13%). Within the medium risk group soil N_2O EF for crop residues with synthetic N is reported to be 0.59 (± 0.27%), and consequently RF_NS_{CRN} is estimated to be 0.28 (Table 1).

In the Rochette et al. (2008), the EF_Topo was further adjusted based on estimates of freeze thaw emission. Field measurements of N_2O flux using chambers in Eastern Canada are usually made during the snow-free period (Gregorich et al. 2005). Seasonal freezing can induce N_2O emissions during the spring thaw (Wagner-Riddle et al. 2017; Pennock et al. 2005). Rochette et al. (2008) reported mean N_2O emissions during the winter and spring thaws in southern Ontario to be 1.2 kg N_2O-N ha^{-1} (Wagner-Riddle et al. 2007; Wagner-Riddle and Thurtell 1998). Recent studies have indicated that there are important emissions occurring during the winter months and in particular during spring thaws (Brin et al. 2018; Chantigny et al. 2016; Wagner-Riddle et al. 2017). Most studies reporting large N_2O emissions associated with spring thaws are based on micrometeorological measurements (Desjardins et al. 2010, Wagner-Riddle et al. 2007, Wagner-Riddle et al. 2017), though the same observations have been made with chambers (Brin et al. 2018; Chantigny et al. 2016). It is clear from these studies that the application of N to these fields influences emissions. However, it is difficult to identify the origin of N emitted as N_2O from either applied N or crop residues, what emissions are already accounted for in estimates of indirect emissions and further to identify what the background emissions would be in a natural environment, as denitrification could be expected in all environments during periods of soil saturation. At this time, it is not possible to adjust the EF_Topo using a literature based correction factor that is based on these limited studies.

When the Rochette et al. (2008) methodology was implemented, the IPCC Good Practice Guidance (IPCC 2003) did not include emissions resulting from the decay of native SOC. In the 2006 IPCC Guidelines this source is included and therefore with the implementation of these guidelines, it is likely that soil N_2O emissions from summer fallow as estimated by Rochette et al. (2008) overlap with those from the soil N mineralization associated with losses of SOC (IPCC 2006). Therefore, it is proposed that soil N_2O emissions from summer fallow as estimated in the previous method be eliminated.

Conclusions

The type of empirical approach defined by this methodological framework requires detailed climate, soil and crop management information. The approach involves the creation of N source specific EFs that take into account the unique combination of climatic, edaphic, topographic and management conditions for a specific region, such as, in the case of Canada, the ecodistrict. The method proposes simple ways to stratify, weight and apply key factors that are regionally specific and known to influence N_2O emissions. It is spatially scalable and allows the user to approach the calculations based on the scale of the information that they have. For example, if the approach is applied at a continental scale, soil and management data could be developed for any country and as a result could provide estimates considering climate, soil variations, using the same empirical standards. For other regions however, the empirical relationships would need to be rebuilt based on local research as we recognize that the empirical RFs are not universal. The most obvious example of this is the fact that tillage is observed to have different effects on soil N_2O emissions in Western and Eastern Canada. The application of this method in Canada provides a very effective approach to incorporate the large body of research carried out in Canada and known factors that influence emissions in the different regions of Canada in a spatially consistent and transparent manner so that key changes in regional crop management over time are quantified and understood at the national scale. Though this proposed approach improves the accuracy of the emission factors that modulate N_2O emissions from spring-based N applications, future work is still required to develop adjustments to factors associated with winter and spring-thaw emissions for fall-based manure and synthetic N applications.

Appendix A

Appendix A. An example of calculations of soil nitrous oxide emissions for an ecodistrict in Eastern and Western Canada

Site Specific Emission Factor Development			Site Specific Emission Factor Development		
		Note			Note
Ecodistrict No.	567		Ecodistrict No.	825	
Region	Eastern Canada		Region	Western Canada	
Township	Southern Ontario		Township	South-Western Saskatchewan	
Weather Information			Weather Information		
Growing season precipitation, P, mm	520		Growing season precipitation, P, mm	260	
Growing season evapotranspiration, PE, mm	610		Growing season evapotranspiration, PE, mm	635	
P/PE	0.85		P/PE	0.41	
Soil Texture, FR_TX			Soil Texture, FR_TX		
Coarse, FR_TX$_{j=C,}$ fraction	0.04		Coarse, FR_TX$_{j=C,}$ fraction	0.00	
Medium, FR_TX$_{j=M,}$ fraction	0.85		Medium, FR_TX$_{j=M,}$ fraction	1.00	
Fine, FR_TX$_{j=F,}$ fraction	0.11		Fine, FR_TX$_{j=F,}$ fraction	0.00	
Fraction of Conservation Tillage Adopted in the Ecodistrict, FR_Till, fraction	0.66		Fraction of Conservation Tillage Adopted in the Ecodistrict, FR_Till, fraction	0.99	
Ecodistrict-based moisture dependent N_2O EF, EF_CT, kg N_2O-N kg^{-1} N	0.008	Eqn. 1	Ecodistrict-based moisture dependent N_2O EF, EF_CT, kg N_2O-N kg^{-1} N	0.002	Eqn. 1
Fraction of lowland soil in the ecodistrict, RF_Topo, fraction	0.08		Fraction of lowland soil in the ecodistrict, RF_Topo, fraction	0.07	
Ecodistrict-based soil N_2O EF adjusting for topograph, EF_Topo, kg N_2O-N kg^{-1} N	0.009	Eqn. 2	Ecodistrict-based soil N_2O EF adjusting for topograph, EF_Topo, kg N_2O-N kg^{-1} N	0.003	Eqn. 2
Soil texture ratio factor, RF_TX (unitless)	0.71	Eqn. 3	Soil texture ratio factor, RF_TX (unitless)	1.00	Eqn. 3
Soil Texture			Soil Texture		
Coarse, RF_TX$_{j=C,}$ unitless	0.49		Coarse, RF_TX$_{j=C,}$ unitless	NA	
Medium, RF_TX$_{j=M,}$ unitless	0.49		Medium, RF_TX$_{j=M,}$ unitless	NA	
Fine, RF_TXj=$_{F,}$ unitless	2.55		Fine, RF_TXj=$_{F,}$ unitless	NA	
Ecodistrict-based and soil texture adjusted N_2O EF, EF_Base, kg N_2O-N kg^{-1} N	0.006	Eqn. 4	Ecodistrict-based and soil texture adjusted N_2O EF, EF_Base, kg N_2O-N kg^{-1} N	0.003	Eqn. 4
IPCC Defaults or Country-specific EFs			**IPCC Defaults or Country-specific EFs**		
Soil N2O EF from volatilized NH_3-N and redeposition, EF_4, kg N2O-N kg^{-1} N	0.01	IPCC (2006)	Soil N_2O EF from volatilized NH_3-N and redeposition, $EF_{4,}$ kg N_2O-N kg^{-1} N	0.01	IPCC (2006)
Soil N2O EF from leached N, EF_5, kg N_2O-N kg^{-1} N	0.0075	IPCC (2006)	Soil N_2O EF from leached N, $EF_{5,}$ kg N_2O-N kg^{-1} N	0.0075	IPCC (2006)
Soil N2O EF from manure N deposited on PRP, $EF_{k=PRP}$, kg N_2O-N kg^{-1} N	0.0063	Rochette et al. (2014)	Soil N_2O EF from manure N deposited on PRP, $EF_{k=PRP,}$ kg N_2O-N kg^{-1} N	0.0004	Lemke et al. (2012)
N to N2O conversion factor, unitless	1.6		N to N_2O conversion factor, unitless	1.6	
Fraction of N leaching in the ecodistrict, FR_Leach, fraction	0.25	Eqn. 19	Fraction of N leaching in the ecodistrict, FR_Leach, fraction	0.11	Eqn. 19
Management Ratio Factors and Parameters			**Management Ratio Factors and Parameters**		
Nitrogen Sources			Nitrogen Sources		
Synthetic N fertilizers, RF_NS$_{k=SN,}$ unitless	1.00		Synthetic N fertilizers, RF_NS$_{k=SN,}$ unitless	1.00	
Organic N fertilizers, RF_NS$_{k=ON,}$ unitless	0.84		Organic N fertilizers, RF_NS$_{k=ON,}$ unitless	0.84	
Crop residue N, RF_NS$_{k=CRN,}$ unitless	0.28		Crop residue N, RF_NS$_{k=CRN,}$ unitless	0.28	
Tillage Practice			Tillage Practice		
Conservation tillage over conventional tillage, RF_Till, unitless	1.05		Conservation tillage over conventional tillage, RF_Till, unitless	0.73	
Crop Type			Crop Type		
Perennial crop over annual crop, RF_CS, unitless	0.19		Perennial crop over annual crop, RF_CS, unitless	0.19	
Irrigation			Irrigation		
Fraction of irrigation in the Ecodistrict, FR_MM, fraction	0.004		Fraction of irrigation in the Ecodistrict, FR_MM, fraction	0.002	
Irrigation emission ratio factor, RF_MM, unitless	1.6	Eqn. 7	Irrigation emission ratio factor, RF_MM, unitless	5.3	Eqn. 7
Nitrogen Input and Distribution			**Nitrogen Input and Distribution**		
Quantity of Activity Data That impacts Emissions			Quantity of Activity Data That impacts Emissions		
The amount of synthetic N fertilizers applied on annual crops, kg N	12715898	Eqn. 10	The amount of synthetic N fertilizers applied on annual crops, kg N	20435957	Eqn. 10
The amount of synthetic N fertilizers applied on perennial crops, kg N	186312	Eqn. 10	The amount of synthetic N fertilizers applied on perennial crops, kg N	412163	Eqn. 10
The quantity of manure N applied on annual crops, kg N	7052351	Eqn. 8	The quantity of manure N applied on annual crops, kg N	1040501	Eqn. 8
The quantity of manure N applied on perennial crops, kg N	103330	Eqn. 8	The quantity of manure N applied on perennial crops, kg N	224578	Eqn. 8
The quantity of manure N deposited on pasture, range and paddock by grazing animals, kg N	93503	Eqn. 9	The quantity of manure N deposited on pasture, range and paddock by grazing animals, kg N	181210	Eqn. 9
CN Ratio	11		CN Ratio	11	
The amount of net losses in SOC through decomposition in the ecodistrict, kg C	29736463		The amount of net losses in SOC through decomposition in the ecodistrict, kg C	0	
The amount of crop residual N in the ecodistrict, kg N	9049860	Eqn. 11	The amount of crop residual N in the ecodistrict, kg N	20098644	Eqn. 11
The area of cultivated organic soils, ha	0	No cultivated organic soils in the ecodistrict	The area of cultivated organic soils, ha	0	No cultivated organic soils in the ecodistrict
The amount of leached N from applications of synthetic N fertilizers, applied manure N, crop residue N, as well as manure N deposited on PRP by grazing animals, kg N	8273213	Eqn. 18	The amount of leached N from applications of synthetic N fertilizers, applied manure N, crop residue N, as well as manure N deposited on PRP by grazing animals, kg N	5236992	Eqn. 18
The amount of volatilized N from applications of synthetic N fertilizers, applied manure N as well as manure N deposited on PRP by grazing animals, kg N	2672070	Eqn. 17	The amount of volatilized N from applications of synthetic N fertilizers, applied manure N as well as manure N deposited on PRP by grazing animals, kg N	2215682	Eqn. 17
Estimates of Soil Nitrous Oxide Emissions by Sources			**Estimates of Soil Nitrous Oxide Emissions by Sources**		
Synthetic N fertilizers, $N_2O_{k=SN,}$ kg N_2O	123448	Eqn. 13	Synthetic N fertilizers, $N_2O_{k=SN,}$ kg N_2O	94591	Eqn. 13
Animal manure N applied as fertilizers, $N_2O_{k=ON}$, kg N_2O	57541	Eqn. 13	Animal manure N applied as fertilizers, $N_2O_{k=ON}$, kg N_2O	4227	Eqn. 13
Animal manure N deposited on pasture, range and paddock, $N_2O_{k=PRP}$, kg N_2O	926	Eqn. 9	Animal manure N deposited on pasture, range and paddock, $N_2O_{k=PRP}$, kg N_2O	122	Eqn. 9
Crop residual N, $N_2O_{k=CRN}$, kg N_2O	24532	Eqn. 15	Crop residual N, $N_2O_{k=CRN}$, kg N_2O	25949	Eqn. 15
Losses of soil organic carbon induced by changes in management practices, $N_2O_{k=SOC,}$ kg N_2O	7328	Eqn. 14	Losses of soil organic carbon induced by changes in management practices, $N_2O_{k=SOC,}$ kg N_2O	0	Eqn. 14
Cultivation of organic soils, $N_2O_{k=OS,}$ kg N_2O	0	IPCC (2014)	Cultivation of organic soils, $N_2O_{k=OS,}$ kg N_2O	0	IPCC (2014)
Conservation tillage, N_2O_Till, kg N_2O	6783	Eqn. 16	Conservation tillage, N_2O_Till, kg N_2O[a]	-33261	Eqn. 16
Irrigation, N_2O_MM, kg N_2O	496	Eqn. 15	Irrigation, N_2O_MM, kg N_2O	1256	Eqn. 15
Leaching of N from all N sources, N_2O_Leach, kg N_2O	97506	Eqn. 18	Leaching of N from all N sources, N_2O_Leach, kg N_2O	61722	Eqn. 18
Volatilization of ammonia from all sources, N_2O_ATD, kg N_2O	41990	Eqn. 17	Volatilization of ammonia from all sources, N_2O_ATD, kg N_2O	34818	Eqn. 17

[a]negative value indicates that conservation tillage on the Canadian praries reduces soil N_2O emissions compared with conventional tillage.

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