Journal of Cleaner Production 234 (2019) 895–911

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Inventories of methane and nitrous oxide emissions from animal and crop farms of 69 municipalities in Alberta, Canada

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ARTICLE INFO

Article history:
Received 21 March 2019
Received in revised form
19 June 2019
Accepted 23 June 2019
Available online 25 June 2019

Handling Editor: Prof. Jiri Jaromir Klemeš

Keywords:
Fertilizer distribution
Nitrous oxide
Methane
Emissions
IPCC inventory

ABSTRACT

Spatially explicit, accurate inventories of greenhouse gas (GHG) emissions are of primary importance when calculating the carbon footprint, identifying sources and sinks, pricing carbon pollution, and creating policy that is effective in reducing emissions. However, there are few reports available on methane and nitrous oxide emissions from each type of livestock and crop in all counties of the province due to a lack of statistical data of sub-categories, such as the different fertilizer quantities used in each crop in the county. Because fertilizer input is the most significant factor for N_2O emissions from agricultural soils, how to best distribute the total fertilizer mass to a crop-specific fertilizer rate for each county is a major challenge in agricultural management. In this study, authors developed a crop-specific method correlating the recommended fertilizer rate and planted area of each crop for a reasonable distribution of total fertilizer mass to fertilizer rate. This is based on a balance between the sum of fertilizer used in all crops and the total fertilizer mass used by each municipality. Using this method, our calculations in 69 municipalities in the province of Alberta, Canada showed that the fertilizer rate for each crop was reasonably distributed from the total fertilizer mass of a municipality: less than 170 kg-N ha^{-1}. The obtained fertilizer rates for each crop in 69 municipalities were used in GHG inventories using IPCC 2006 tier 1 and 2 methods. The total CH_4 and N_2O emissions from agriculture in all of Alberta in 2011 were 328 Gg CH_4 yr^{-1} and 23.5 Gg N_2O yr^{-1}, respectively. The southeastern municipalities generally emitted more CH_4 and N_2O than northwestern municipalities. The southern municipality of Lethbridge emitted the largest amount of CH_4 and N_2O of all municipalities (25.3 Gg CH_4 yr^{-1} (7.70% of total CH_4 of entire Alberta) and 1.26 Gg N_2O yr^{-1} (5.40% of total N_2O of entire Alberta), respectively). This was due to its largest cattle population (414,627 head) and larger synthetic fertilizer input (32,111 ton-N) and planted area (206,077 ha). The second largest CH_4 and N_2O emission source was also located at the south. The Taber municipality emitted 15.8 Gg CH_4 yr^{-1} (4.80% of total CH_4 of entire Alberta) and 1.14 Gg N_2O yr^{-1} (4.80% of total N_2O of entire Alberta), respectively.

1. Introduction

Since the industrial revolution, human activities have increased greenhouse gas (GHG) concentrations in the atmosphere, resulting in climate change with severe consequences for human life and economic development. It has been determined that the main GHGs include carbon oxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Their concentrations in the atmosphere are heavily affected by human activities, such as combustion of carbon fuels (coal, oil and natural gas), agricultural production of both livestock and crop farms, land use changes and deforestation. The contribution of each GHG to climate change is expressed by its Global Warming Potential (GWP) according to IPCC (Stocker, 2014), which indicates a gas' capacity to absorb radiation and its lifetime in the atmosphere based on CO_2 capacity (Eilers, 2010). Thus, GWPs of CH_4 and N_2O are, respectively, 25 and 300 of CO_2 equivalents for the first 100 years of their lifetime in the atmosphere, based on GWP as one of CO_2.

While CO_2 emissions can partially be offset by CO_2 uptake in plants, CH_4 and N_2O are not subject to photosynthesis or other direct biological offsets. Therefore, CH_4 and N_2O emitted from agriculture, such as livestock, managed agricultural soils, rice cultivation, burning of savanna, and returned crop residues are GHG net sources (Eggleston et al., 2006). Agricultural soils are

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https://doi.org/10.1016/j.jclepro.2019.06.270
0959-6526/

estimated to contribute about 65% of global N_2O emissions (Reay et al., 2012). Therefore, it is a challenge to reduce GHG emissions as well as maintaining affordable food prices. In Canada, although the combustion of fossil fuels is a major source of GHG emissions, the agricultural activities also result in a relatively large percentage (8%) of CO_2, CH_4 and N_2O emissions (with an additional 3% agricultural fossil fuel and energy use) of Canada's total GHG emissions in 2006 (Janzen, 2008; Weldemichael and Assefa, 2016). The CH_4 emitted from agriculture in Canada originates primarily from enteric fermentation and manure management of livestock production (Eggleston et al., 2006), while N_2O originates from microbial processes of nitrification and denitrification in both livestock and crop farms.

To facilitate the challenge of estimating GHG inventories at the provincial or country level, the Intergovernmental Panel on Climate Change (IPCC) developed standard methods for GHG emission estimations that consist of three tiers, depending on the pursued level of compatibility, transparency and precision (Eggleston et al., 2006). The Tier 1 is the empirical method to calculate CH_4 and N_2O emissions using standardized equations and default emission factors (EFs). The Tier 2 method is based on the Tier 1 empirical equations, but country-specific EF values are used, thereby increasing precision while maintaining the same level of simplicity and empiricism. The Tier 3 method is based on applying well-constrained and recognized process-based models such as DeNitrification- DeComposition (DNDC) model developed (Li et al., 2000) in order to maintain transparency of CH_4 and N_2O emission estimations, as well as to improve their precision and validity at a finer scale. However, it was realized that GHG emissions from agriculture were heavily dependent on spatial and temporal variability (Cardenas et al., 2010), so that this variability has to be considered in GHG inventories. For example, the amount of CH_4 and N_2O released depends on the type, age, and weight of the animals, their different N excretion rates, quality and quantity of the forage, and animal energy expenditures. The country specific emission factors ($EF_{3,4}$) of cattle urine and dung to nitrous oxide emissions were also investigated (Chadwick et al., 2018). They found that the average N_2O $EF_{3,4}$ for urine and dung was 0.0049, which was less than 25% of the IPCC default value. In addition, emission factors vary from region to region due to structural differences in agricultural practices. Therefore, an increasing need to consider spatial heterogeneity exists to resolve GHG emissions at a finer spatial resolution as long as the census data are available. This is especially important for big countries, like Canada, consisting of many provinces and territories with a large geographical scale.

On the other hand, the Canadian federal government has determined to collect a nation-wide carbon tax, beginning at $10 per ton of carbon dioxide equivalent emissions in 2018 and rising to $50 per ton by 2022. Thus, distributions of GHG emissions in each province of Canada and each county (municipalities in Alberta) within the province are a topic of concern because the GHG emissions directly determine tax values. There are many investigations on GHG inventories at national and state (province in Canada) levels (Rochette et al., 2008a, 2008b) because IPCC guidelines were designed for national accounting purposes (Li et al., 2017). But few studies exist at the micro-level, particularly for all counties (all municipalities in Alberta) of a province to the best of our knowledge. An example is the Biswas et al.'s investigation (2017), who reported CH_4 and N_2O emissions of 26 counties in Murshidabad District, West Bengal, India. Another example is the study (Wu et al., 2017), who reported agricultural CO_2-eq emission from cultivation, breeding, and rural living in the farming system of 16 cities in Anhui province, China. One of reasons such a study is lacking is the absence of statistical data of sub-categories within each county. In Canada, Statistics Canada does not collect sub-category data within a county. For example, Statistics Canada collects fertilizer expenses in each county, which can be calculated for the fertilizer mass used in the county, but it does not collect fertilizer expenses used for each crop in a county. Therefore, it is necessary to develop a method: (1) to calculate fertilizer mass from total expenses of purchased fertilizer in municipalities; and (2) to estimate fertilizer mass used for each crop from the total fertilizer mass in a municipality. On the other hand, for an improvement of inventory of GHG emissions from managed agricultural soils, IPCC 2006 (Eggleston et al., 2006) suggested that fertilizer used in a country might be disaggregated by fertilizer type, crop type and climatic regime for major crops. However, this document does not propose a method to conduct this task. A simple method would be using average fertilizer rates for every crop (same fertilizer rate (kg-N ha^{-1}) for each crop) i.e. the total fertilizer mass calculated from (1) divided by the total planted area of all the crops. But this is not crop specific, resulting in emissions data that is only a function of the planted area, not related to crop type. Because fertilizer input is the most important factor in N_2O emissions from managed soils, how to reasonably distribute the total fertilizer mass, based on the total expenses of each county, to each crop is a major challenge for estimation of GHGs emitted from each crop soil.

The general aim of this study is to develop a method for a spatially-explicit estimations of CH_4 and N_2O emissions from animal and crop farms at two levels: county and province wide. For this purpose, the GHG model for the national CH_4 and N_2O inventories in the United Kingdom developed by Wang et al. (2011) will be modified, in which the equations and parameters in the IPCC (1996) were substituted by those of the IPCC 2006 because the 2006 methodology was better than that of 1996 for three major crops: maize, wheat, and soya beans (Smith, 2017). Furthermore, a new method will also be developed to calculate crop specific fertilizer rates from total fertilizer mass. This makes it possible to estimate greenhouse gas emissions from difference crops inputted with different fertilizer rare in all farms to fill a gap of IPCC method. The objectives of this study are:

(1) to collect and re-catalog agricultural data of both animal and crop farms obtained from Statistics Canada and Alberta Agriculture and Forestry;
(2) to develop a reasonable method to distribute total fertilizer mass calculated on the total expenses of each municipality to each crop of that municipality;
(3) to estimate the CH_4 and N_2O emissions from animal and crop farms of 69 municipalities in Alberta, Canada, and at the provincial level based on the available agricultural data from Statistics Canada and Alberta Agriculture and Forestry using methods in objects (1) and (2).

2. Methods

2.1. Study area

Alberta is a western province of Canada with a territory area of 660,000 km^2 (Distribution of Alberta's 64 municipal districts(https://en.wikipedia.org/wiki/List_of_municipal_districts_in_Alberta -/media/File:Alberta%27s_Municipal_Districts.png) (Fig. 1). Agriculture plays a significant role in the province's economy. The province had over five million head of cattle and dairy cows in 2011. Almost one half of all Canadian beef is produced in Alberta, and grain are primary farm crops in central and southern Alberta regions.

Fig. 1. Map of municipalities in Alberta (https://en.wikipedia.org/wiki/List_of_municipal_districts_in_Alberta#/media/File:Alberta%27s_Municipal_Districts.png).

2.2. GHG model

The GHG model developed (Wang et al., 2011) has been designed as an inventory framework for CH_4 and N_2O calculations from agricultural activities. The model code was written with C++ using the parameters and equations of IPCC (1996) and run on Microsoft Visual Studio 2008. In this study, the authors modified the GHG model using the parameters and equations of IPCC 2006. The model consists of two sub-models, one calculated at a local level (69 municipalities in this study), and another aggregating from all local level CH_4 and N_2O emissions to province level CH_4 and N_2O emissions.

2.2.1. CH_4 calculation methods

The CH_4 emitted from enteric fermentation is a by-product of digestive processes in herbivores (Qiao et al., 2014). Although both ruminant animals, such as dairy cows, cattle, and sheep, which digest cellulose, and non-ruminant animals, such as pigs, and horses, produce methane from enteric fermentation, the ruminant animals are a much greater source than non-ruminant animals. Another CH_4 source from livestock farms is manure management systems under anaerobic conditions, including stored manure piles, lagoons, and other liquid treatment systems. However, CH_4 also can be sunk by agricultural soils to reduce its emission (Dutaur and Verchot, 2007).

The agricultural CH_4 emissions in each municipality can be calculated from enteric fermentation and manure management by applying IPCC Tier 1 method in Chapter 10 of the 2006 IPCC Guidelines for National Greenhouse gas Inventories (Eggleston et al., 2006) as follows:

$$CH_{4EorM}^{k} = \sum_{i=1}^{13} \frac{EF^i \times P^i}{10^6} \tag{1}$$

where the superscripts k and i denote municipality and animal type, respectively, CH_{4EorM}^{k} is the emissions from enteric fermentation (CH_{4E}) or manure management (CH_{4M}) of k municipality, respectively (Gg CH_4 yr^{-1}), EF is the corresponding emissions factor (kg CH_4 $head^{-1}$ yr^{-1}), P is the corresponding population of animal (head), and 10^6 is a unit conversion factor (kg Gg^{-1}). According to Statistics Canada and Alberta Agriculture and Forestry, the province of Alberta is divided into 69 municipalities (Fig. 1), where there are mainly 13 types of animals to be raised, i.e. (1) dairy cow, (2) beef cow, (3) dairy heifer, (4) beef heifer, (5) buffalo, (6) pig + wild boar, (7) sheep, (8) goats, (9) camels, (10) horses, (11) elk + deer, (12) other animals, and (13) poultry. The numbers P^i of i type of livestock in k municipality in 2011 required in Equation (3) were obtained and re-cataloged from Statistics Canada and Alberta Agriculture and Forestry (Alberta Agriculture and Rural Development Information Management Division, 2011). The default EF^i values of 13 types of livestock for CH_{4E} and CH_{4M} in North America (Tables 10.11, 10.14, 11.15, and 11.16 in IPCC, 2006) summarized in Table S1. When these data and parameters were input into the GHG model, it calculated CH_{4E}, CH_{4M}, and total methane ($CH_{4E} + CH_{4M}$) for each livestock type and all the livestock types in each municipality in the province of Alberta.

2.2.2. N_2O calculation methods

The direct N_2O emissions from soils are due to applications of both inorganic and organic fertilizers (N), crop residue decomposition when it is returned to soils, cultivation of organic soils, and sewage sludge application. The direct N_2O emissions from animal production include those induced by grazing animals in the fields. The indirect N_2O emissions are due to volatilization (offsite) and re-deposition (at the site) of NH_3, N leaching (e.g. with soil waters), and N run off (e.g. in surface waters) in both animal and crop farms activities.

The microbial processes of nitrification and denitrification producing N_2O can be expressed as (Smith et al., 2003):

$$\text{Nitrification} \qquad \begin{array}{l} NH_4^+ \rightarrow NO \rightarrow NO_2^- \rightarrow NO_3^- \\ \qquad\quad\ \downarrow \qquad \downarrow \\ \qquad\quad NO \quad N_2O\ (Emission) \end{array} \tag{2}$$

and

$$\text{Denitrification} \qquad \begin{array}{l} NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \\ \qquad\qquad\qquad\qquad\quad \downarrow \\ \qquad\qquad\qquad\qquad N_2O\ (Emission) \end{array} \tag{3}$$

both of which are net sources of N_2O (Alvarez et al., 2014). More detailed mechanisms also have been reported (Butterbach-Bahl et al., 2013).

Therefore, the N_2O emissions from agricultural activities involve: (1) direct N_2O emissions from managed soils; (2) direct N_2O emissions from manure management systems of livestock production; (3) indirect N_2O emissions from NH_3 and NO_x volatilization and subsequent offsite deposition, and leaching from managed agricultural soils; and (4) indirect N_2O emissions from NH_3 and NO_x volatilization and subsequent offsite deposition, and leaching from manure manage management systems (Eggleston et al., 2006).

2.2.2.1. Direct N_2O emissions from managed soils. The direct N_2O emissions from managed soils, also called anthropogenic, which are induced by human activities in agricultural ecosystems, come mainly from N inputs including both synthetic and organic fertilizer to soils as well as crop residue decomposition, and from urine and dung inputs to grazed soils. The direct emissions from managed soils in k municipality were calculated from Equations (11.1) of Chapter 11.2.1of the 2006 IPCC Guidelines for National Greenhouse gas Inventories (Eggleston et al., 2006), which includes: (1) nitrogen inputs to managed soils, and (2) nitrogen inputs by grazing animals on pasture, range and paddock:

$$N_2O_D^k - N = N_2O - N_{Ninputs}^k + N_2O - N_{PRP}^k \tag{4}$$

$$N_2O-N^k_{Ninputs}=\sum_{l=1}^{34}\left(F^{k,l}_{SN}+F^{k,l}_{ON}+F^{k,l}_{CR}\right)\times EF_1 \quad (5)$$

$$N_2O-N^k_{PRP}=\sum_{i=1}^{13}\left(F^{k,i}_{PRP,CPP}\times EF_{3PRP,CPP}+F^{k,i}_{PRP,SO}+EF_{3PRP,SO}\right) \quad (6)$$

where superscript l denotes crop type, the subscripts CPP and SO refer to cattle, poultry and pigs, and sheep and other animals, respectively, N_2O_D-N is the annual direct N_2O-N emitted from managed soils (kg N_2O-N yr^{-1}), $N_2O-N_{Ninputs}$ is the annual direct N_2O-N emitted from N applied soils (kg N_2O-N yr^{-1}), N_2O-N_{PRP} is the annual direct N_2O-N emitted from grazed soils inputted by animal urine and dung (kg N_2O-N yr^{-1}), F_{SN} is the annual mass of synthetic fertilizer applied to soils (kg N yr^{-1}), F_{ON} is the annual mass of livestock manure, and other organic N additions applied to soils (kg N yr^{-1}), F_{CR} is the annual mass of N in crop residues returned to soils (kg N yr^{-1}), F_{PRP} is the annual mass of urine and dung N deposited by grazing animals on pasture, range and paddock (kg N yr^{-1}), EF_1 is the emission factor for N_2O emissions from N inputs (kg N_2O-N (kg N input)$^{-1}$) (Table S1 cited from Table 11.1 of IPCC, 2006), and EF_{3PRP} is the emission factor for N_2O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals (kg N_2O-N (kg N input)$^{-1}$) (Table S2 cited from Table 11.1 of IPCC, 2006). In the above equations, two items of (1) annual direct N_2O-N emissions from managed organic soils and (2) emissions from the annual amount of N in mineral soils in the original equation of IPCC 2006 were omitted because of the locking of organic soil data for the former, and no requirement for single year emissions for latter. According to Statistics Canada and Alberta Agriculture and Forestry (Alberta Agriculture and Rural Development Information Management Division, 2011), there are 34 types of plants in Alberta: (1) tame hay and fodder crops, (2) forage seed for seed, (3) soybeans, (4) flaxseed, (5) dry field peas, (6) chick peas, (7) lentils, (8) dry white beans; (9) other dry beans, (10) potatoes, (11) alfalfa and alfalfa mixtures, (12) other legumes, (13) spring wheat, (14) durum wheat; (15) winter wheat, (16) oats, (17) barley, (18) mixed grains, (19) corn for grain, (20) corn for silage, (21) fall rye, (22) spring rye, (23) canola (rapeseed), (24) mustard seed, (25) sunflowers; (26) canary seed; (27) ginseng, (28) buckwheat, (29) sugar beets, (30) caraway seed, (31) triticale, (32) other field crops, (33) total vegetables (excluding greenhouse vegetables), and (34) total area of fruits, berries and nuts (producing and non-producing). The first and second types combined are named as forage, the third to twelve as legumes, and the thirteen to thirty fourth as other in outputs of GHG model.

The total fertilizer expenses ex^k (C$) in k municipalities is equal to sum of j type of fertilizer price per kg $fp^{k,j}$ (C$ (kg fertilizer)$^{-1}$) multiplying mass of j type of fertilizer used $F^{k,j}_{fSN}$ (kg-fertilizer):

$$ex^k=\sum_{j=1}^{3}fp^{k,j}F^{k,j}_{fSN} \quad (7)$$

But $F^{k,j}_{fSN}$ is equal to total fertilizer mass F^{k}_{fSN} (kg-fertilizer) multiplying fraction r^j (dimensionless) of j type of fertilizer in three fertilizers:

$$F^{k,j}_{fSN}=F^{k}_{fSN}\times r^j \quad (8)$$

Substituting Equation (8) into Equation (7) produces

$$ex^k=F^k_{SN}\sum_{j=1}^{3}fp^{k,j}\times r^j \quad (9)$$

where the item $\sum_{j=1}^{3}fp^{k,j}r^j$is the average fertilizer price for three fertilizers. Once $fp^{k,j}$ and r^j are known, F^k_{SN} and $F^{k,j}_{SN}$ can be calculated. However, $F^{k,j}_{SN}$ should be converted into kg −N substitution for kg fertilizer as a requirement of Equation (5). So $F\text{-}N^{k,j}_{SN}$ (kg-N) and $F\text{-}N^{k}_{SN}$ (kg-N) are, respectively.

$$F^{k,j}_{SN}=F^{k,j}_{fSN}\times c^j_N \quad (10)$$

$$F^k_{SN}=\sum_{j=1}^{3}F^{k,j}_{SN} \quad (11)$$

where superscript j denotes fertilizer type, C_N is the nitrogen content in each fertilizer (kg N (kg fertilizer)$^{-1}$), F^k_{SN} is the sum of nitrogen contents in three fertilizers in k municipality (kg-N).

Because there is no data about the fertilizer rate used for a specific crop in each municipality, how to reasonably distribute the fertilizer used in a municipality for each crop is a challenge. The authors correlated the fertilizer rate in each crop with the product of recommended fertilizer rate of each crop proposed by Alberta Agriculture and the actual planted area of each crop in each municipality. According to mass balance, the fertilizer ($F^{k,l}_{SN}$) (kg-N) used in l cope of k municipality is equal to the actual fertilizer rate ($R^{k,l}_{ac}$) (kg-N ha^{-1}) used multiplying the planted area $A^{k,l}$ (ha) of l type of crop:

$$F^{k,l}_{SN}=R^{k,l}_{ac}A^{k,l} \quad (12)$$

and the total fertilizer (F^k_{SN}) (kg-N) used in k municipality is equal to the sum of actual fertilizer rate (R^k_{ac}) (kg-N ha^{-1}) used multiplying the planted area A^k (ha) of l type of crop:

$$F^k_{SN}=\sum_{k=1}^{69}\sum_{l=1}^{34}\left(R^l_{ac}A^{k,l}\right) \quad (13)$$

Assuming the actual used fertilizer rate ($R^{k,l}_{ac}$) is linearly relative to the recommended fertilizer rate (R^l_r (dimensionless)) of l type of crop proposed by Alberta Agriculture, and it does not change with respect to the municipality. The authors deleted the superscript k in the actual used fertilizer rate ($R^{k,l}_{ac}$) of Equation (14) as this assumption.

$$R^l_{ac}=a\times R^l_r \quad (14)$$

where the letter a is a proportional constant (dimensionless), R_r is the recommended fertilizer rate by Alberta Agriculture (Alberta Fertilizer Guide) (kg-N ha^{-1}), and A is the planted area (ha). Substituting Equation (14) into Equations (12) and (13) produces

$$F^{k,l}_{SN}=aR^k_rA^{k,l} \quad (15)$$

$$F^k_{SN}=a\sum_{k=1}^{69}\sum_{l=1}^{34}\left(R^l_rA^{k,l}\right) \quad (16)$$

Equation (15) is divided by Equation (16). It produces

$$F_{SN}^{k,l} = \frac{R_r^l \times A^{k,l}}{\sum_{k}^{69} \sum_{l=1}^{34} \left(R_r^l \times A^{k,l}\right)} F_{SN}^k \quad (17)$$

$$r^{k,l} = \frac{R_r^l \times A^{k,l}}{\sum_{k}^{69} \sum_{l=1}^{34} \left(R_r^l \times A^{k,l}\right)} \quad (18)$$

where $r^{k,l}$ is the fraction of product of fertilizer rate used and planted area for l type of crop in k municipality in sum of above products, which is a function of crop type and municipality. Because F_{SN}^k, R_r^l, and $A^{k,l}$ can be obtained from Equation (10) and Alberta Agriculture respectively, $F_{SN}^{k,l}$ can be calculated. Furthermore, the actual fertilizer rate ($R_{ac}^{k,l}$) (kg-N ha^{-1}) of l type of crop in k municipality (kg-N ha^{-1}) is

$$R_{ac}^{k,l} = \frac{F_{SN}^{k,l}}{A^{k,l}} \quad (19)$$

It is noted that the actual fertilizer rate ($R_{ac}^{k,l}$) changes with crop type and municipality.

It was estimated that 65% of manure were returned to agricultural soils as organic fertilizers in Canada (Rochette et al., 2008a). So the item $F_{ON}^{k,l}$ used in l type of crop of k municipality, respectively, in Equation (5) is equal to

$$F_{ON}^{k,l} = 0.65 \times r^l \sum_{i=1}^{13} Nex^i \times P^{k,i} \quad (20)$$

and the total organic fertilizer F_{ON}^k in k municipality is

$$F_{ON}^k = \sum_{l=1}^{34} F_{ON}^{k,l} \quad (21)$$

where Nex is the manure rate produced by i type of livestock (kg-N head^{-1} yr^{-1}), which only is a function of livestock type i, not related to municipality.

According to IPCC 2006 (Eggleston et al., 2006), the annual mass of N in crop residues (above-ground and below-ground) returned to soils (F_{CR}) in k municipality can be calculated by the following equations:

$$F_{CR}^k = \sum_{l=1}^{34} A^{k,l} \times R_{BG}^l \times N_{BG}^l \quad (22)$$

where R_{BG} is the ratio of below-ground residues dry matter (A_{GDM}) to harvested yield (kg D.M. (kg D. M)$^{-1}$) (D.M. refers to Dried Matter), and N_{BG} is the N content of below-ground residues (kg N (kg D.M.)$^{-1}$. It is noted that both R_{BG} and N_{BG} are only a function of crop type l, not related to municipality. In above Equation (22), the authors have omitted the item of burnt inputted N because the factor $F_{racRenew}$ (fraction of total crop area under crop l that is renewed annually) is equal to one following the IPCC 2006 assumption. Although IPCC 2006 gives the default factors N_{BG}, and R_{BG} in Table 11.2 and an empirical equation of AG_{DM}, the Canada-specific R_{BG} were calculated in this study based on data of below-ground residues dry matter and harvested yield for each Canadian crop (Janzen et al., 2003). But the authors used the default N_{BG} of IPCC 2006 (Table 1). Thus, F_{CR}^k in Equation (22) can be calculated.

As described above, because 65% of manure were returned to agricultural soils as organic fertilizers, 35% of N content of total manure was considered the urine and dung N deposited on pasture, range and paddock by grazing animals. Because the authors cannot distinguish the N contents of CPP (cattle, poultry and pigs) or SO (sheep and other animals) from the total manures, the $N_2O - N_{PRP}$ in k municipality in Equation (5) is simplified as

$$N_2O - N_{PRP}^k = 0.35 \times R^l \times \left(\sum_{i=1}^{13} Nex^i P^{k,i}\right) \times EF_{3PRP,CPP} \quad (23)$$

2.2.2.2. Direct N_2O emissions from manure management. According to IPCC 2006 (Eggleston et al., 2006), the direct N_2O emissions from manure management in k municipality can be calculated using the following equation:

$$N_2O_{mm}^k = \left\{ \sum_{m=1}^{5} \left[\sum_{i=1}^{13} \left(P^i \times Nex^i \times MS^{i,m}\right) \right] \times EF_3^m \right\} \times \frac{44}{28} \quad (24)$$

where the superscript m is the index of manure management system, N_2O_{mm} is the direct N_2O emissions from manure management in k municipality (kg N_2O yr^{-1}), Nex^i is the annual average N excretion per head of i type of livestock in the province of Alberta (kg N head^{-1} yr^{-1}), $MS^{i,m}$ is the fraction of annual nitrogen excretion for i type of livestock that is managed in m type of manure management system in k municipality (Table S3), which is a function of both animal type i and manure management system type m, EF_3^m is the emission factor for direct N_2O emissions from m type of

Table 1
Recommended fertilizer rate (R_r) (kg-N ha^{-1}), ratio (R_{BG}) of below-ground residues dry matter to harvested yield (dimensionless), and N content (N_{BG}) of below-ground residues of main crops (dimensionless) in Alberta.

Crop type	R_r	R_{BG}	N_{BG}	$R_{BG}XN_{BG}$
Hay and fodder crops	45	0.9503	0.0220	0.0209
Forage seed for seed	80	1.0000	0.0120	0.0120
Soybeans	0	0.2560	0.0080	0.0020
Flaxseed	65	0.4444	0.0120	0.0053
Dry field peas	0	0.8684	0.0100	0.0087
Chick peas	0	0.8684	0.0220	0.0191
Lentils	0	0.5333	0.0080	0.0043
Dry white beans	0	0.5000	0.0080	0.0040
Other dry beans	0	0.5000	0.0080	0.0040
Potatoes	130	0.5625	0.0140	0.0079
Alfalfa and alfalfa mixtures	0	0.2881	0.0190	0.0055
other legumes	0	0.2560	0.0220	0.0056
Spring wheat	55	0.4633	0.0090	0.0042
Durum wheat	80	0.4633	0.0090	0.0042
Winter wheat	55	0.4566	0.0090	0.0041
Oats	55	0.7246	0.0080	0.0058
Barley	96	0.5654	0.0140	0.0079
Mixed grains	55	0.6364	0.0090	0.0057
Corn for grain	140	0.3958	0.0070	0.0028
Corn for silage	140	6.3333	0.0070	0.0443
Fall rye	56	0.6000	0.0110	0.0066
Spring rye	56	0.6000	0.0110	0.0066
Canola (rapeseed)	85	0.7037	0.0100	0.0070
Mustard seed	85	0.5556	0.0100	0.0056
Sunflowers	120	0.7037	0.0100	0.0070
Canary seed	55	1.0000	0.0100	0.0100
Ginseng	80	1.0000	0.0100	0.0100
Buckwheat	80	0.4633	0.0090	0.0042
Sugar beets	80	1.5000	0.0140	0.0210
Caraway seed	55	1.5000	0.0100	0.0150
Triticale	55	0.4633	0.0090	0.0042
Other field crops (46)	55	1.5000	0.0090	0.0135
Total vegetables	120	1.2727	0.0090	0.0115
Total area of fruits, berries and nuts	120	1.5000	0.0090	0.0135
Other crop	55	1.5000	0.0090	0.0135
Other crop	55	1.5000	0.0090	0.0135

manure management system (kg N_2O-N (kg N)$^{-1}$), and 44/28 is the conversion of $N_2O\text{-}N_{mm}$ emissions to N_2O_{mm} emissions.

$$Nex^i = N^i_{rate} \times \frac{TAM^i}{100} \times 365 \quad (25)$$

where N^i_{rate} is the default N excretion rate (kg N (1000 kg head mass)$^{-1}$ day^{-1}), and TAM^i is the typical animal mass for i type of livestock (kg head^{-1}).

2.2.2.3. Indirect N_2O emissions from NH_3 and NO_x volatilization and subsequent offsite deposition, and leaching from agricultural soils. The N_2O emissions from atmospheric deposition of N volatilized from managed soil in k municipality are estimated using

$$N_2O^k_{ATD} = \left[\left(F^k_{SN} \times Frac_{GASF}\right) + \left(F^k_{ON} + F^k_{PRP}\right) \times Frac_{GASM}\right] \times EF_4 \times \frac{44}{28} \quad (26)$$

which is a tier 2 method according to IPCC 2006 (Eggleston et al., 2006), where $N_2O_{ATD}\text{–}N$ is the annual amount of N_2O-N produced from atmospheric deposition of N volatilized from managed soils (kg N_2O yr^{-1}), $Frac_{GASF}$ is the fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx (kg N volatilized (kg of N applied)$^{-1}$ (Table S3 cited from Table 11.3 of IPCC, 2006), $Frac_{GASM}$ is the fraction of applied organic N fertilizer materials (F_{ON}) and of urine and dung N deposited by grazing animals (F_{PRP}) that volatilizes as NH_3 and NOx (kg N volatilized (kg of N applied or deposited)$^{-1}$) (Table S3 cited from Table 11.3 of IPCC, 2006), EF_4 is the emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (kg $N-N_2O$ (kg NH_3-N + NOx–N volatilized)$^{-1}$) (Table S3 cited from Table 11.3 of IPCC, 2006).

2.2.2.4. Indirect N_2O emissions from manure management. Indirect N_2O emissions from manure management include two processes: (1) volatilization of N from manure management (Equation (27)), and (2) leaching and runoff from manure management (Equation (28)). The latter is belong to a tier 2 method according to IPCC 2006 (Eggleston et al., 2006).

$$N_2O^k_{Gmm} = \left\{\sum_{m=1}^{5}\left[\sum_{i=1}^{13}\left(P^{k,i} \times Nex^i \times MS^{i,m}\right) \times \left(\frac{Frac_{GasMS}}{100}\right)^{i,m}\right] \times \right\} EF_4 \times \frac{44}{28} \quad (27)$$

where N_2O_{Gmm} is the indirect N_2O emissions due to volatilization of N from manure management in k municipality (kg N_2O yr^{-1}), EF_4 is the emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces (kg N_2O-N (kg NH_3-N + NOx-N volatilized)$^{-1}$) (Table S3), and $Frac_{GasMS}$ is the percentage of managed manure nitrogen for i type of livestock that volatilizes as NH_3 and NOx in the m type of manure management system (%).

$$N_2O^k_{Lmm} = \left\{\sum_{m=1}^{5}\left[\sum_{i=1}^{13}\left(P^{k,i} \times Nex^i \times MS^{i,m}\right) \times \left(\frac{Frac_{leachMS}}{100}\right)^{i,m}\right] \times \right\} EF_5 \frac{44}{28} \quad (28)$$

where N_2O_{Lmm} is the indirect N_2O emissions due to leaching and runoff from manure management in k municipality (kg N_2O yr^{-1}), $Frac_{leachMS}$ is the percentage of managed manure nitrogen losses for i type of livestock due to runoff and leaching during solid and liquid storage of manure (Table S3), and EF_5 is the emission factor for N_2O emissions from nitrogen leaching and runoff (kg N_2O-N (kg N leached and runoff)$^{-1}$) (Table S3). All the above equations were used to calculate various emissions in a municipality. For the entire province of Alberta, all the emissions calculated from these equations should be the sum of emissions from 69 municipalities. An overall calculation framework is shown Fig. 2.

It should be mentioned that the Tier 1 approach has several limitations. Because the Tier 1 used simple equations and IPCC default *EFs*. This approach cannot resolve variation of emission

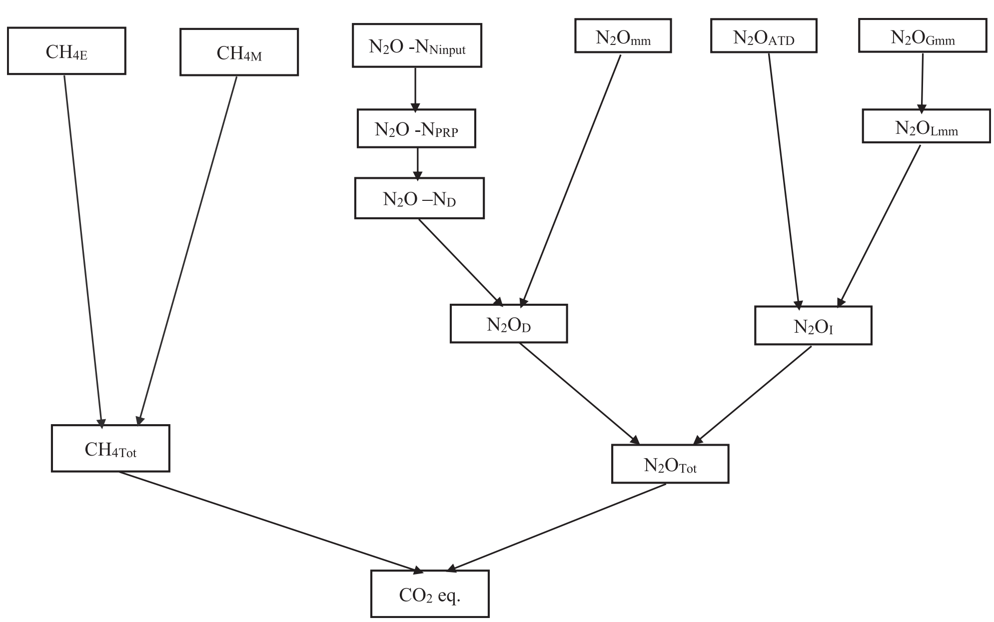

Fig. 2. An overall calculation framework in which N_2Oi is the indirect N_2O emissions.

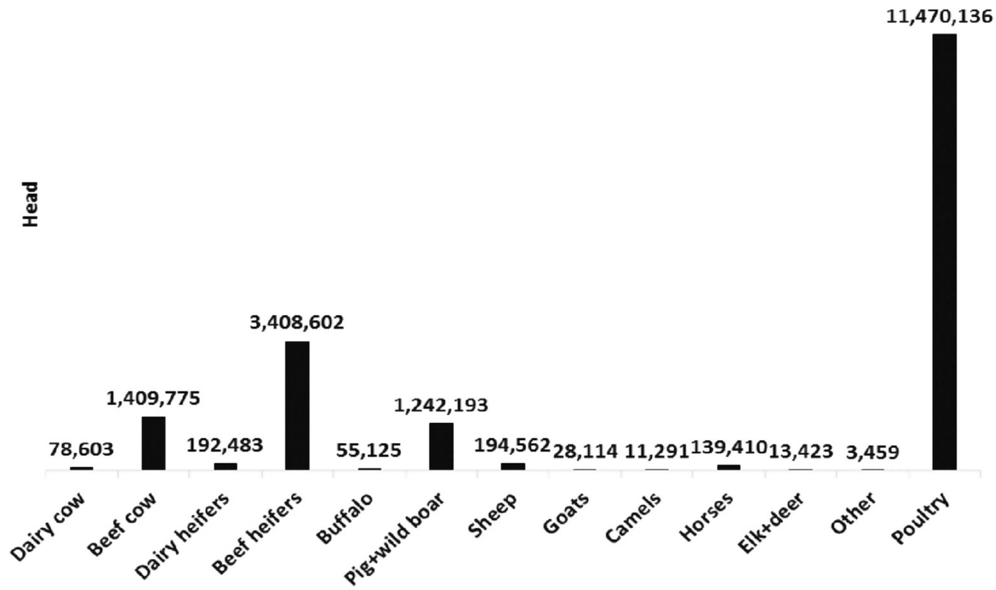

Fig. 3. Populations of 13 type of livestock of 2011 in Alberta.

factors from region to region due to soil heterogeneity, climate change and structural differences in agricultural practices. Furthermore, the accuracy of the assessment depends greatly on spatial resolution of agricultural census data, such as animal type, crop type and manure management. Therefore, an increasing availability of data at a finer spatial resolution is especially important to reduce uncertainties for big countries, like Canada, consisting of many parishes, counties, provinces and territories with a large geographical scale.

3. Results and discussion

3.1. Case study of 69 municipalities in Alberta based on collected agricultural data

Poultry has the largest population among 13 types of livestock in Alberta (11,470,136 head), followed by beef cows (beef cow + beef heifers) (4,818,377 head), and dairy cows (dairy cow + dairy heifers) (271,086 head) (Fig. 3). However, the N excretion (*Nex*) of poultry only is 1.93% (0.85/44) and 0.88% (0.85/97) of beef cows and dairy cows, respectively, and poultry's emission factors of EF_e and EF_m for CH_4 are 0 and 0.08 kg CH_4 head^{-1} yr^{-1}, respectively, but the EF_e and EF_m of beef and dairy cows are as high as 53 and 1 kg CH_4 head^{-1} yr^{-1}for beef cows, and 128 and 48 kg CH_4 head^{-1} yr^{-1}for dairy cows, respectively. Therefore, the beef cows and dairy cows were the main contributors of CH_4 emissions in Alberta. Two special areas (C, B) raised the maximum and second maximum dairy cow + dairy heifers (39,662 and 35,791 head, respectively) followed by Lacombe County (14,633) (Table 2). However, there was the maximum population of cattle cow + cattle heifers in Lethbridge County (414,627 head) followed by Taber County (265,193 head) and Vulcan County (195,321 head) (Table 2). The populations of dairy cow and cattle cows in these counties were significant for direct N_2O (N_2O_{mm}) emissions from manure management of livestock in the entire province of Alberta (N_2O_{mmTot}). Among all the four direct and indirect N_2O emissions in agricultural activities in Alberta, the managed soils contribution was much more significant than those from livestock (See the next section in detail). In addition, the Vulcan County has the maximum planted area among 69 municipalities in Alberta (354,065 ha), followed by Wheatland County (308,917 ha), and Vermilion River County (290,465 ha) (Table 3). The first and second counties are located at the southern part of Alberta, close to Lethbridge County. Lethbridge and its vicinity are the most important agricultural areas in Alberta.

Alberta Agriculture and Rural (Development Agriculture and Forestry) provided the expenses (Table 3) of fertilizer and lime purchases of 69 municipalities and prices of three main synthetic fertilizers: urea (46-0-0) C$606 per ton, anhydrous ammonia (82-0-0) C$949 per ton, and monoammonium phosphate (11-51-0) C$800 in 2011, in which the numbers 46, 82, and 11 denote nitrogen contents in each fertilizer. Because the purchased lime mass was much less than the fertilizer mass (Alberta Agriculture and Rural Development Information Management Division, 2011), the expenses of fertilizer and lime were approximately equal to those of fertilizer. Alberta Agriculture and Rural Development (Agriculture and Forestry) also provided the fractions of each of three fertilizers used: 0.475, 0.186, and 0.339 for urea, anhydrous ammonia, and monoammonium phosphate, respectively. Thus, using Equations (7)–(11), the authors obtained the synthetic fertilizer masses used in 2011 of 69 municipalities in Alberta (Table 3). The maximum synthetic fertilizer mass used was 21,647 ton-N in Taber County, followed by 21,082 ton-N in Vulcan County, and 20,064 ton-N in Wheatland County, which implied that these municipalities would make larger contributions of N_2O emissions in Alberta. The total fertilizer mass sued in the entire province of Alberta was 544,271 ton-N, which was greater than that (467,754 ton-N) used in 1998 reported by Alberta Agriculture and Rural Development (Agriculture and Forestry). This report also pointed out the total fertilizer mass increased annually from 353,469 ton-N in 1985 to 467,754 ton-N in 1998, which increased 32.3%. For same period of 13 years from 1998 to 2011, the fertilizer mass increased 16.4% based on our calculation.

The authors calculated the synthetic fertilizer rates of 34 types of crops from the total synthetic fertilizer mass of each municipality using the method the authors developed (Equations (12)–(18)). The distributions of synthetic fertilizer rates in three typical municipalities: Lethbridge (49°38′ N, 112°47′ W), Lacombe (52°27′ N, 113°45′ W), and Beaverlodge (55°13′ N, 119°24′ W) (belonging to Grande Prairie County), which represent three primary areas of agricultural production in Southern, Central, and Northern Alberta,

Table 2
Populations of dairy cow + dairy heifers (head), cattle cow + cattle heifers (head), fractions of CH_{4Tot}, N_2O_{Tot}, F_{SN} and N_2O_{mm} (all in dimensionless) of 69 municipalities in entire Alberta.

Municipality	Dairy cow + heifers	Beef cow + heifers	CH_{4Tot}	N_2O_{Tot}	F_{SN}	N_2O_{mm}
Athabasca	696	48,666	0.009	0.010	0.010	0.009
Barrhead	5120	74,511	0.016	0.016	0.015	0.016
Beaver	770	47,033	0.010	0.016	0.019	0.010
Big Lakes	159	31,203	0.006	0.005	0.005	0.006
Bighorn	0	7516	0.001	0.000	0.000	0.001
Birch Hills	0	20,432	0.004	0.013	0.019	0.005
Bonnyville	4488	58,930	0.013	0.008	0.006	0.012
Brazeau	376	28,362	0.005	0.002	0.001	0.005
Calgary	63	571	0.000	0.001	0.002	0.000
Camrose	2119	60,009	0.012	0.023	0.027	0.015
Cardston	2372	85,496	0.018	0.020	0.021	0.019
Clear Hills	112	22,037	0.004	0.006	0.007	0.004
Clearwater	1604	76,867	0.015	0.008	0.004	0.015
Cypress	626	149,382	0.026	0.018	0.014	0.027
Edmonton	24	161	0.000	0.000	0.001	0.000
Fairview	3339	3565	0.002	0.006	0.009	0.001
Flagstaff	4101	52,994	0.011	0.021	0.027	0.010
Foothills	372	122,480	0.021	0.017	0.014	0.023
Forty Mile	2458	59,320	0.012	0.021	0.025	0.012
Grande Prairie	4269	60,786	0.014	0.017	0.020	0.013
Greenview	2239	41,266	0.009	0.008	0.007	0.008
Kneehill	1237	80,340	0.016	0.028	0.034	0.019
Lac La Biche	8788	9230	0.006	0.003	0.002	0.004
Lac Ste. Anne	586	69,925	0.012	0.008	0.006	0.013
Lacombe	14,633	90,898	0.026	0.023	0.022	0.025
Lamont	2331	33,372	0.007	0.014	0.018	0.007
Leduc	8961	51,427	0.013	0.015	0.016	0.013
Lesser Slave River	5679	6078	0.004	0.001	0.001	0.002
Lethbridge	12,975	414,627	0.077	0.054	0.029	0.081
Mackenzie	17	16,684	0.003	0.009	0.012	0.003
Minburn	578	88,375	0.016	0.020	0.023	0.016
Mountain View	4623	103,013	0.020	0.022	0.024	0.022
Newell	1595	144,544	0.026	0.023	0.017	0.027
Northern Lights	29	18,633	0.004	0.010	0.013	0.004
Northern Sunrise	4585	4345	0.003	0.005	0.007	0.002
Paintearth	805	69,211	0.013	0.010	0.008	0.013
Parkland	2362	42,991	0.009	0.009	0.009	0.009
Peace	3563	4948	0.003	0.003	0.004	0.002
Pincher Creek	566	99,683	0.019	0.013	0.010	0.020
Ponoka	13,149	110,381	0.027	0.017	0.013	0.027
Provost	6162	89,221	0.018	0.013	0.011	0.017
Ranchland	0	14,364	0.002	0.001	0.000	0.003
Red Deer	8146	137,205	0.030	0.029	0.029	0.030
Rocky View	1011	133,787	0.024	0.023	0.022	0.026
Saddle Hills	160	27,513	0.005	0.010	0.013	0.005
Smoky Lake	52	41,319	0.007	0.008	0.009	0.007
Smoky River	3644	5295	0.003	0.018	0.027	0.002
Special Area	530	142,827	0.024	0.012	0.005	0.025
Special Area	35,791	40,284	0.026	0.011	0.007	0.015
Special Area	39,662	47,960	0.029	0.011	0.006	0.017
Spirit River	125	1490	0.000	0.002	0.003	0.000
St. Paul	304	87,034	0.015	0.012	0.011	0.016
Starland	641	34,537	0.007	0.012	0.014	0.008
Stettler	2586	106,999	0.021	0.017	0.014	0.022
Strathcona	822	13,959	0.003	0.007	0.009	0.003
Sturgeon	2542	22,524	0.006	0.017	0.022	0.010
Taber	2942	265,193	0.048	0.048	0.041	0.051
Thorhild	13,602	15,121	0.010	0.008	0.009	0.006
Two Hills	2402	37,909	0.008	0.012	0.014	0.008
Vermilion River	290	145,117	0.026	0.028	0.030	0.027
Vulcan	2530	195,321	0.036	0.039	0.041	0.037
Wainwright	1136	66,317	0.014	0.016	0.019	0.014
Warner	2826	88,283	0.019	0.023	0.022	0.021
Westlock	2166	74,830	0.015	0.020	0.024	0.015
Wetaskiwin	3622	72,030	0.014	0.014	0.013	0.015
Wheatland	1391	160,827	0.028	0.034	0.038	0.030
Willow Creek	1836	174,828	0.032	0.023	0.019	0.034
Woodlands	10,560	11,116	0.008	0.003	0.001	0.004
Yellowhead	1236	54,875	0.010	0.006	0.003	0.010
Total	271,086	4,818,377	1.000	1.000	1.000	0.999

Table 3
Synthetic fertilizer mass used (N-T), planted area (ha), and expense (C$) of fertilizer purchases in 69 municipalities.

Municipality	Fertilizer (N-T)	Planted Area (ha)	Fertilizer purchases (C$)
Athabasca County No. 12	5811	111,146	9,617,287
Barrhead County No. 11	8220	108,168	13,604,236
Beaver County	10,699	177,151	17,706,752
Big Lakes	2849	60,003	4,715,899
Bighorn No. 8	151	2408	249,301
Birch Hills County	10,560	101,500	17,477,077
Bonnyville No. 87	3517	93,689	5,821,377
Brazeau County	513	36,897	849,032
Calgary	1182	7048	1,956,894
Camrose County No. 22	15,045	234,693	24,899,231
Cardston County	11,651	168,287	19,282,118
Clear Hills No. 21	4085	97,629	6,760,678
Clearwater County	2199	78,169	3,639,582
Cypress County	7479	182,424	12,377,826
Edmonton	413	2368	683,362
Fairview No. 136	5239	85,422	8,670,726
Flagstaff County	15,474	157,056	25,610,337
Foothills No. 31	7706	157,700	12,753,027
Forty Mile County No. 8	13,875	282,697	22,963,232
Grande Prairie County No. 1	10,772	225,309	17,827,274
Greenview No. 16	4034	122,664	6,676,357
Kneehill County	18,436	246,129	30,511,675
Lac La Biche County	1088	32,180	1,799,895
Lac Ste. Anne County	3218	100,238	5,325,080
Lacombe County	12,068	162,719	19,973,400
Lamont County	10,121	149,746	16,750,803
Leduc County	8769	150,541	14,513,227
Lesser Slave River No.124	456	17,071	755,289
Lethbridge County	13,929	206,077	23,053,618
Mackenzie No. 23	6983	129,287	11,556,748
Minburn County No. 27	12,441	187,531	20,590,961
Mountain View County	13,144	201,370	21,754,192
Newell County No. 4	8845	145,462	14,639,534
Northern Lights No. 22	7317	141,058	12,110,478
Northern Sunrise County	4111	67,502	6,803,242
Paintearth County No. 18	4247	140,623	7,028,861
Parkland County	5175	62,424	8,564,349
Peace No. 135	2164	32,373	3,582,321
Pincher Creek No. 9	5698	95,472	9,429,626
Ponoka County	6718	123,941	11,119,058
Provost No. 52	6193	136,421	10,250,228
Ranchland No. 66	61	1980	100,156
Red Deer County	15,672	225,144	25,936,947
Rocky View No. 44	11,960	201,121	19,793,763
Saddle Hills County	7062	143,859	11,688,196
Smoky Lake County	4872	82,988	8,063,392
Smoky River No. 130	15,690	196,710	25,968,045
Special Area No. 2	2397	138,125	3,966,388
Special Area No. 3	3452	199,584	5,712,944
Special Area No. 4	2829	126,741	4,682,416
Spirit River No. 133	1961	27,391	3,245,021
St. Paul County No. 19	6084	132,483	10,069,772
Starland County	7615	152,634	12,602,541
Stettler County No. 6	7558	182,163	12,508,286
Strathcona County	5145	57,087	8,514,598
Sturgeon County	12,284	145,443	20,330,723
Taber	21,647	252,229	35,827,205
Thorhild County No. 7	5270	68,224	8,721,861
Two Hills County No. 21	8089	149,503	13,387,099
Vermilion River No. 24	15,913	290,465	26,337,324
Vulcan County	21,082	354,073	34,891,473
Wainwright No. 61	10,395	113,932	17,203,368
Warner County No. 5	11,605	244,347	19,206,958
Westlock County	13,283	157,665	21,984,265
Wetaskiwin County No. 10	7226	121,470	11,958,729
Wheatland County	20,064	308,971	33,206,130
Willow Creek No. 26	9730	166,605	16,103,325
Woodlands County	831	25,223	1,375,447
Yellowhead County	1902	62,247	3,148,408

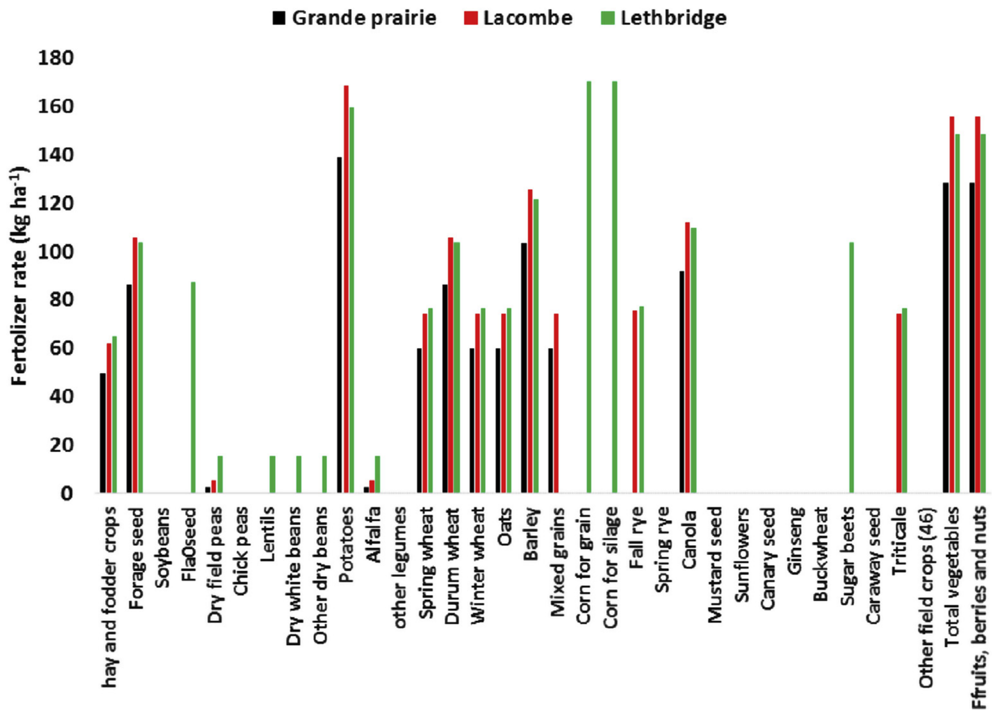

Fig. 4. Fertilizer rates calculated of 34 types of crop in three municipalities: Grande Prairie, Lacombe, and Lethbridge.

respectively (Li et al., 2016), are shown in Fig. 4. It can be found that the synthetic fertilizer rates of 34 types of crops in these three municipalities were reasonably distributed: all the fertilizer rates are less than 170 kg-N ha^{-1}. Another calculation the authors made (data not shown) also indicted that, if only the recommended fertilizer rate was considered (not including the planted area), the rates of some crops would be as high as several thousand kg-N per hectare, which was obviously unreasonable.

3.2. Methane and nitrous oxide emissions from animal and crop farms

Calculations of CH_4 and N_2O emissions from enteric fermentation (CH_{4E}), manure management (CH_{4M}), manure management systems (N_2O_{mm}), organic fertilizer (F_{ON}) crop residue decay (F_{CR}), synthetic fertilizers (F_{SN}), volatilization and offsite deposition (F_{ATD}), leaching and runoff (F_L), and their totals CH_{4Tot} and N_2O_{Tot} for each main animal type and plant type in Alberta are shown in Table 4. It can be found that the most significant generator of enteric methane was cattle cows (258.41 Gg yr^{-1}) followed by dairy cows 32.38 Gg yr^{-1}), resulting from a large difference in their populations, i. e. 4,818,377 heads of cattle versus 271,086 heads of dairy. Unlike CH_{4E}, the main generator for manure CH_4 emissions was pigs with 40.7% of total CH_{4M} because its EF (10 kg CH_4 $head^{-1}$ yr^{-1}) is 10 times that (1 kg CH_4 $head^{-1}$ yr^{-1}) of cattle cows (Table S1), although its population was lower than that of cattle cows, followed by dairy cows with 36.5% of total CH_{4M}, but CH_{4M} of sum of dairy and beef cows was 55.7% of total CH_{4M}, higher than that of pigs. In addition, CH_{4M} values of both cows and pigs were much larger than that of the other animal types. In comparison with other developed countries, such as France, CH_{4M} of both dairy and beef cows was lower than 80% (10.8 (dairy + cattle)/13.5 (total) %) of total CH_{4M}, and CH_{4M} from pig was higher than 15.6% (2.1 (pig)/13.5 (total) %) of total CH_{4M} (Gac et al., 2007). In both cases of Alberta and France, the majority of CH_{4M} emissions originated from a combination of cows and pigs, and much smaller CH_{4M} did from the other animal types. The larger CH_{4M} emissions from cows and pigs compared to the other animal types were not only due to their populations and weight, but also to prevailing liquid-based manure management systems for pigs and cows in North America, in which the stored manure were anaerobically digested to produce CH_4. Therefore, the calculated CH_{4Tot} (CH_{4E} and CH_{4M}) in Alberta

Table 4
Methane and nitrous oxide emissions (Gg yr^{-1}) in the province of Alberta, i. e. from enteric fermentation (CH_{4E}), manure management (CH_{4M}, N_2O_{mm}, organic N fertilizer (F_{ON}), crop residues N returned to soil (F_{CR}), synthetic N fertilizer (F_{SN}), NH_3 and NOx volatilization and offsite deposition (F_{ATD}), leaching (F_L), and total emissions (CH_{4Tot}, N_2O_{Tot}).

Type	CH_{4E}	CH_{4M}	N_2O_{mm}	F_{ON}	F_{CR}	F_{SN}	F_{ATD}	F_L	CH_{4Tot}	N_{Tot}
Dairy	32.38	11.14	0.30	0.17	0.00	0.00	0.00	0.06	43.52	0.54
Cattle	258.41	5.87	4.35	1.39	0.00	0.00	0.04	0.48	264.27	6.27
Pigs	1.86	12.42	0.21	0.14	0.00	0.00	0.00	0.05	14.29	0.41
Sheep	1.70	0.04	0.03	0.01	0.00	0.00	0.00	0.00	1.74	0.05
Poultry	0.00	1.03	0.19	0.06	0.00	0.00	0.00	0.02	1.03	0.27
Other animals	2.99	0.05	0.12	0.04	0.00	0.00	0.00	0.01	3.04	0.18
Forage	0.00	0.00	0.00	0.00	0.00	0.54	0.05	0.12	0.00	0.71
Legumes	0.00	0.00	0.00	0.00	0.00	0.19	0.02	0.04	0.00	0.25
Other crops	0.00	0.00	0.00	0.00	2.27	9.47	0.95	2.13	0.00	14.83
Total	297.3	30.55	5.22	1.82	2.27	10.20	1.07	2.93	327.9	23.50

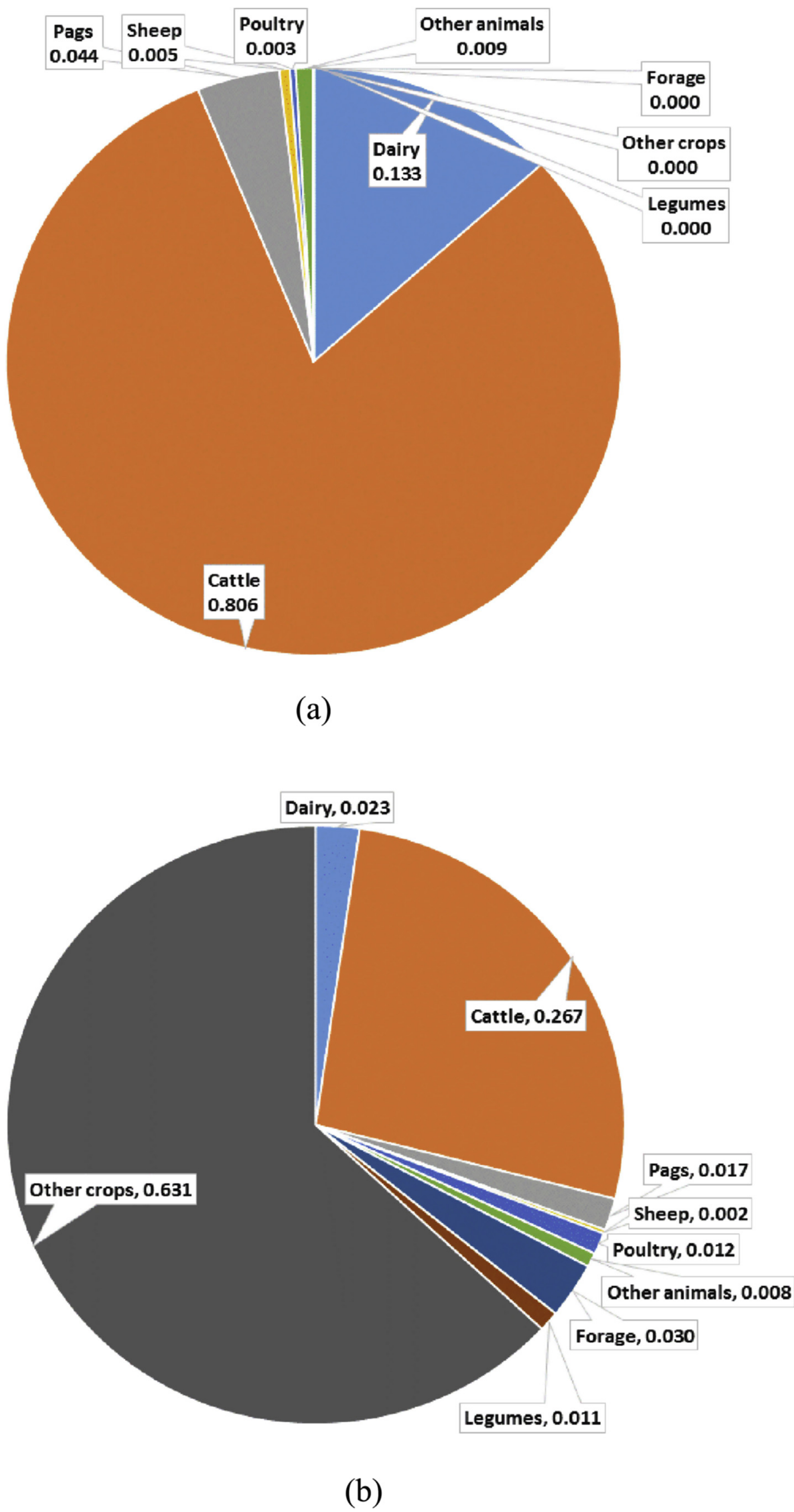

Fig. 5. CH_{4Tot} (a) and N_2O_{Tot} (b) fractions of 9 categories in total emissions of Alberta province.

Table 5
Methane and nitrous oxide emissions (Gg yr^{-1}) in 69 counties in AB, i. e. from enteric fermentation (CH_{4E}), manure management (CH_{4M}, N_2O_{mm}, organic N fertilizer (F_{ON}), crop residues N returned to soil (F_{CR}), synthetic N fertilizer (F_{SN}), NH_3 and NOx volatilization and offsite deposition (F_{ATD}), leaching (F_L), and total emissions (CH_{4Tot}, N_2O_{Tot}).

Municipality	dCH_{4E}	CH_{4M}	N_2O_{mm}	F_{ON}	F_{CR}	F_{SN}	F_{ATD}	F_L	CH_{4Tot}	N_{Tot}
Athabasca No. 12	2.78	0.09	0.05	0.02	0.02	0.11	0.01	0.03	2.87	0.23
Barrhead No. 11	4.65	0.57	0.08	0.03	0.04	0.15	0.02	0.04	5.22	0.37
Beaver County	2.69	0.48	0.05	0.02	0.03	0.20	0.02	0.05	3.17	0.38
Big Lakes	1.74	0.08	0.03	0.01	0.01	0.05	0.01	0.02	1.81	0.12
Bighorn No. 8	0.42	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.42	0.01
Birch Hills County	1.15	0.27	0.02	0.01	0.02	0.19	0.02	0.05	1.42	0.31
Bonnyville No. 87	3.83	0.30	0.06	0.02	0.01	0.07	0.01	0.02	4.13	0.19
Brazeau County	1.66	0.07	0.03	0.01	0.00	0.01	0.00	0.01	1.73	0.06
Calgary	0.04	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.05	0.03
Camrose No. 22	3.54	0.37	0.08	0.03	0.06	0.28	0.03	0.07	3.91	0.54
Cardston County	5.04	0.82	0.10	0.04	0.04	0.22	0.02	0.06	5.85	0.47
Clear Hills No. 21	1.27	0.05	0.02	0.01	0.01	0.07	0.01	0.02	1.31	0.14
Clearwater County	4.47	0.35	0.08	0.03	0.01	0.04	0.00	0.02	4.82	0.18
Cypress County	8.06	0.32	0.14	0.05	0.03	0.15	0.02	0.05	8.38	0.42
Edmonton	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.01
Fairview No. 136	0.62	0.16	0.01	0.00	0.02	0.09	0.01	0.02	0.79	0.15
Flagstaff County	3.36	0.25	0.05	0.02	0.04	0.28	0.03	0.07	3.61	0.49
Foothills No. 31	6.73	0.18	0.12	0.04	0.03	0.15	0.02	0.05	6.91	0.40
Forty Mile No. 8	3.47	0.44	0.06	0.02	0.05	0.26	0.03	0.07	3.91	0.48
Grande Prairie No. 1	4.21	0.46	0.07	0.02	0.03	0.20	0.02	0.05	4.67	0.40
Greenview No. 16	2.67	0.19	0.04	0.02	0.02	0.07	0.01	0.02	2.86	0.18
Kneehill County	4.54	0.67	0.10	0.03	0.05	0.34	0.04	0.09	5.21	0.65
Lac La Biche	1.65	0.43	0.02	0.01	0.00	0.02	0.00	0.01	2.09	0.06
Lac Ste. Anne	3.93	0.11	0.07	0.02	0.02	0.06	0.01	0.02	4.04	0.20
Lacombe County	6.84	1.63	0.13	0.05	0.03	0.23	0.02	0.07	8.47	0.54
Lamont County	2.18	0.17	0.03	0.01	0.03	0.18	0.02	0.05	2.35	0.33
Leduc County	3.87	0.54	0.07	0.02	0.04	0.16	0.02	0.04	4.41	0.35
Lesser Slave River	1.08	0.29	0.01	0.01	0.00	0.01	0.00	0.00	1.37	0.03
Lethbridge County	23.6	1.61	0.42	0.14	0.25	0.30	0.03	0.12	25.25	1.26
Mackenzie No. 23	0.93	0.03	0.02	0.01	0.02	0.13	0.01	0.03	0.96	0.21
Minburn No. 27	4.94	0.24	0.09	0.03	0.04	0.23	0.02	0.06	5.18	0.47
Mountain View	6.20	0.32	0.11	0.04	0.04	0.25	0.03	0.07	6.52	0.53
Newell No. 4	7.92	0.46	0.14	0.05	0.10	0.17	0.02	0.05	8.38	0.53
Northern Lights	1.11	0.05	0.02	0.01	0.02	0.13	0.01	0.03	1.16	0.22
Northern Sunrise	0.86	0.24	0.01	0.00	0.01	0.07	0.01	0.02	1.10	0.12
Paintearth No. 18	3.84	0.37	0.07	0.02	0.02	0.08	0.01	0.03	4.21	0.23
Parkland County	2.78	0.15	0.05	0.02	0.01	0.09	0.01	0.03	2.93	0.20
Peace No. 135	0.73	0.18	0.01	0.00	0.01	0.04	0.00	0.01	0.91	0.07
Pincher Creek No. 9	5.55	0.68	0.10	0.04	0.02	0.11	0.01	0.04	6.23	0.32
Ponoka County	7.64	1.23	0.14	0.05	0.02	0.13	0.01	0.05	8.86	0.41
Provost No. 52	5.54	0.39	0.09	0.03	0.02	0.12	0.01	0.04	5.93	0.31
Ranchland No. 66	0.77	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.79	0.02
Red Deer County	8.51	1.31	0.16	0.06	0.06	0.30	0.03	0.09	9.82	0.69
Rocky View No. 44	7.40	0.36	0.13	0.04	0.04	0.23	0.02	0.07	7.76	0.53
Saddle Hills County	1.62	0.08	0.03	0.01	0.02	0.13	0.01	0.03	1.70	0.23
Smoky Lake County	2.27	0.06	0.04	0.01	0.01	0.09	0.01	0.02	2.34	0.19
Smoky River	0.79	0.19	0.01	0.00	0.04	0.28	0.03	0.06	0.98	0.43
Special Area No. 2	7.67	0.16	0.13	0.04	0.02	0.05	0.01	0.03	7.83	0.27
Special Area No. 3	6.79	1.78	0.08	0.03	0.04	0.07	0.01	0.03	8.57	0.26
Special Area No. 4	7.65	1.95	0.09	0.04	0.04	0.06	0.01	0.03	9.60	0.26
Spirit River No. 133	0.10	0.01	0.00	0.00	0.00	0.03	0.00	0.01	0.11	0.05
St. Paul No. 19	4.77	0.12	0.08	0.03	0.02	0.11	0.01	0.03	4.89	0.29
Starland County	1.98	0.37	0.04	0.02	0.03	0.14	0.01	0.04	2.34	0.28
Stettler No. 6	6.21	0.73	0.11	0.04	0.04	0.15	0.02	0.05	6.94	0.40
Strathcona County	0.91	0.04	0.02	0.01	0.01	0.09	0.01	0.02	0.95	0.16
Sturgeon County	1.61	0.42	0.05	0.02	0.03	0.22	0.02	0.06	2.03	0.41
Taber	14.6	1.23	0.26	0.09	0.19	0.42	0.04	0.13	15.81	1.14
Thorhild No. 7	2.60	0.68	0.03	0.01	0.01	0.10	0.01	0.03	3.27	0.19
Two Hills No. 21	2.38	0.16	0.04	0.01	0.03	0.15	0.02	0.04	2.54	0.28
Vermilion River	8.02	0.42	0.14	0.05	0.05	0.31	0.03	0.08	8.44	0.66
Vulcan County	10.8	0.88	0.19	0.07	0.09	0.41	0.04	0.12	11.69	0.92
Wainwright No. 61	3.81	0.70	0.08	0.03	0.02	0.19	0.02	0.05	4.51	0.39
Warner No. 5	5.15	1.11	0.11	0.04	0.08	0.22	0.02	0.06	6.26	0.54
Westlock County	4.37	0.49	0.08	0.03	0.04	0.24	0.03	0.06	4.86	0.48
Wetaskiwin No. 10	4.48	0.26	0.08	0.03	0.03	0.13	0.01	0.04	4.73	0.32
Wheatland County	8.80	0.50	0.16	0.05	0.07	0.38	0.04	0.10	9.29	0.81
Willow Creek	9.93	0.66	0.18	0.06	0.03	0.19	0.02	0.06	10.59	0.54
Woodlands County	1.99	0.53	0.02	0.01	0.00	0.02	0.00	0.01	2.52	0.06
Yellowhead County	3.17	0.10	0.05	0.02	0.02	0.04	0.00	0.01	3.27	0.15
Total	297	30.55	5.22	1.82	2.27	10.2	1.07	2.93	328	23.5

originated predominantly from cows (93.8%) followed by pigs (4.6%), unlike other developed countries such as the United Kingdom where sheep populations were larger and CH_{4Tot} from sheep was 22.8% of total CH_{4Tot}, but CH_4 from cows was 73.1% of total CH_{4Tot}, both of which were 7.78 and 24.9 times of CH_4 from pigs (2.9% of total CH_4) (Wang et al., 2011). Fig. 5a summarized the CH_{4Tot} ($CH_{4E} + CH_{4M}$) contributions of 9 categories (dairy cow, cattle cow, pig, sheep, poultry, other animals, forage, legumes, and other crops) of animals and crops in total CH_{4Tot} of the entire province of Alberta. The maximum CH_{4Tot} contribution was the cattle cows (80.6%) followed by dairy cows (13.3%), and pigs (4.4%). Furthermore, CH_{4ETot} contributed 90.7% (297/328%) of total CH_{4Tot} (Table 4), which was higher than that (74.1% = 10,610/14,311%) of 2007 in India (Sharma et al., 2011).

The calculated total N_2O in Alberta originated predominantly from other crops (14.83 Gg yr^{-1}), followed by cows (cattle and dairy) (6.81 Gg yr^{-1}) (Table 4). The calculated total N_2O emissions (15.79 Gg yr^{-1}, i.e. 67.2% of N_2O_{Tot} in the entire province of Alberta) from all crops (forage, legumes, and other crops) was much larger than that (7.72 Gg yr^{-1}, i.e. 32.8% of N_2O_{Tot} in the entire province of Alberta) from all animals (dairy cow, cattle cow, pig, sheep, poultry, other animals). For comparison, the contribution of crops to the total N_2O in the United Kingdom was reported to be 71.3% (57.6 Gg yr^{-1}) versus 30.0% (37.1 Gg yr^{-1}) from cows (Wang et al., 2011). The order of main contributors to the calculated N_2O emissions from plants in Alberta was the synthetic fertilizer inputs (10.2 Gg yr^{-1}), manure management 5.22 Gg yr^{-1}), leaching and runoff from manure management (2.93 Gg yr^{-1}), and crop residues (2.27 Gg yr^{-1}). It was reported that low N_2O emissions from Western Canada, including Alberta (<1000 kg CO_2e ha^{-1}, i. e. = 3.33 kg N_2O ha^{-1}) compared to those from Eastern Canada (>2000 kg CO_2e ha^{-1}, i. e. = 6.67 kg N_2O ha^{-1}) were due to: (1) predominant types of crops grown in western provinces, such as wheat, which require less synthetic N fertilization (Eilers, 2010), and (2) more humid soils in the eastern provinces than western provinces (Rochette et al., 2008b), which leads lower water-filled pore space (WFPS) and lower microbial activities of nitrification and denitrification in western soils. Fig. 5b shows the N_2O_{Tot} contributions of 9 categories of animal and crops in the total N_2O_{Tot} of the entire province of Alberta. The maximum N_2O_{Tot} contribution was from other crops (63.1%) followed by cattle cow (26.7%), and forage (3.0%). The combined CH_{4Tot} and N_2O_{Tot} emissions from agricultural activities in Alberta in 2011 were 328 Gg CH_4 yr^{-1} and 23.5 Gg N_2O yr^{-1}, respectively. The latter is equivalent to 15.0 Gg N_2O–N yr^{-1}, which was slight less than the average emissions (15.8 Gg N_2O–N yr^{-1}) between 1990 and 2005 in Alberta reported by (Rochette et al., 2008a). The equivalent CO_2 (8200 Gg eq. CO_2 yr^{-1}) of CH_{4Tot} was higher than that (7050 Gg eq. CO_2 yr^{-1}) from N_2O_{Tot} in 2011 in Alberta. The latter was about 86% percentage of the former.

3.3. Methane and nitrous oxide emissions from 69 municipalities of Alberta

Calculated CH_{4E}, CH_{4M}, N_2O_{mm}, F_{ON}, F_{CR}, F_{SN}, F_{ATD}, F_L, and their totals CH_{4Tot} and N_2O_{Tot} for each main animal type and plant type in 69 municipalities of Alberta are shown in Table 5. The largest emissions of CH_4 and N_2O in 69 municipalities of Alberta in 2011 were emitted from Lethbridge County in Table 5 (25.25 Gg CH_4 yr^{-1} and 1.26 Gg N_2O y^{-1}, respectively), which were 7.70% and 5.40% of the total CH_4 and N_2O emissions of 69 municipalities (Table 2). The second large emissions of CH_4 and N_2O occurred at Taber County (15.8 Gg CH_4 yr^{-1} and 1.14 Gg N_2O y^{-1}, respectively), which are 4.82% and 4.85% of the total CH_4 and N_2O emissions of 69 municipalities (Table 2). From Fig. 1 it can be seen that both municipalities

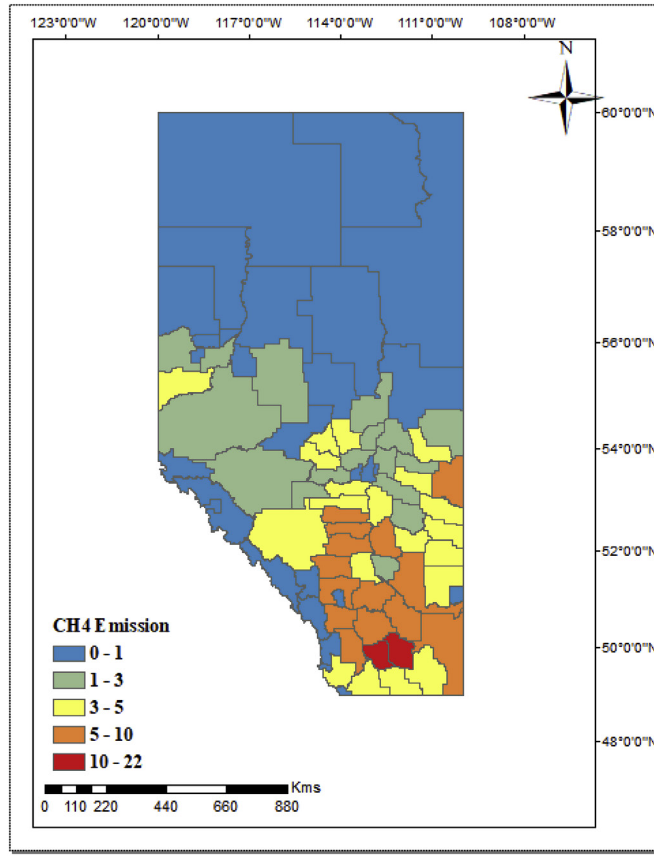

Fig. 6. CH_{4Tot} distribution in 69 municipalities.

of Lethbridge and Taber are neighbors, both of which are the most impartment areas of agricultural production in Alberta. It was also found in Figs. 6 and 7, and Table 5 that there was an increasing pattern of CH_{4Tot} and N_2O_{Tot} emissions from the Northwestern municipalities to the Southeastern municipalities. For example, CH_{4Tot} and N_2O_{Tot} emissions of Lethbridge (South), Lacombe (Center), and Beaverlodge (Northwest) were 25.25 Gg CH_4 yr^{-1} (631 CO_2 eq. Gg yr^{-1}) and 1.26 Gg N_2O y^{-1} (378 CO_2 eq. Gg yr^{-1}), 8.47 Gg CH_4 yr^{-1} (212 CO_2 eq. Gg yr^{-1}) and 0.54 Gg N_2O y^{-1} (162 CO_2 eq. Gg yr^{-1}), and 4.67 Gg CH_4 yr^{-1} (117 CO_2 eq. Gg yr^{-1}) and 0.40 Gg N_2O y^{-1} (120 CO_2 eq. Gg yr^{-1}), respectively. The possible causes are: (1) the warmer weather in the southern area, leading to relatively longer plant-growing seasons, and (2) a geographical transition from boreal forest in the Northwestern area to prairies in the Southeastern area, leading to larger crop areas, larger grasslands and pastures, and greater density of livestock populations. According to Alberta carbon tax 2018: C$30 per ton of carbon dioxide emissions (Alberta's path to a carbon tax: A timeline), Lethbridge, Lacombe, and Beaverlodge municipalities should pay carbon tax C$30.3 million, C$11.2 million, and C$7.1 million, respectively. In addition, the direct N_2O emissions (19.5 Gg N_2O yr^{-1} and 83.0% of the total for all of Alberta), including N_2O_{mm}, F_{ON}, F_{SN}, and F_{CR}, in entire province of Alberta, was much larger than that (4.0 Gg N_2O y^{-1} and 17.0% of total for all of Alberta) of the indirect emissions, including F_{ATD} and F_L. The percentages of direct N_2O emissions in the total N_2O emissions were very close to the corresponding data (0.535/0.652% = 82.0%) of 2012 in Murshidabad District, West Bengal reported by Biswas et al. (2017), but less than that (16.91/28.09% = 65.6%) of 2011 in the United Kingdom (Milne et al., 2014). Among direct N_2O emissions in all of Alberta, the synthetic fertilizer

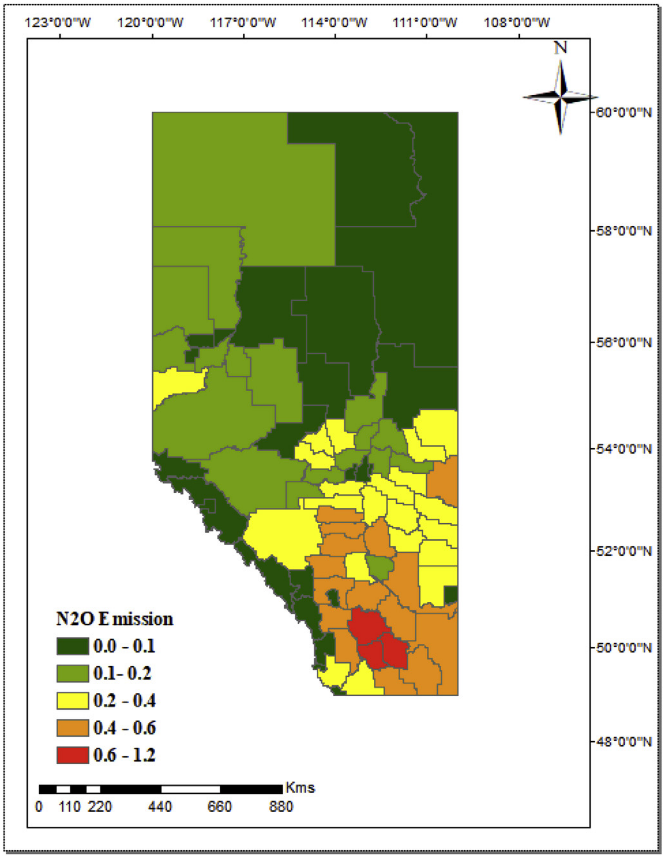

Fig. 7. N_2O_{Tot} distribution in 69 municipalities.

(F_{SN}) contributes the largest part of the entire N_2O emissions (10.2 Gg N_2O yr^{-1}, 52.3% of total entire emission), second is N_2O_{mm} (5.22 Gg N_2O yr^{-1}, 28.6% of total entire emissions), and the third F_{CR} (2.27 Gg N_2O yr^{-1}, 11.6% of total entire emissions), which implies that decreasing synthetic fertilizer input to soils can greatly reduce N_2O emissions. On the other hand, because F_{SN} is proportional to the recommended fertilizer rate (R_r) in Equation (15) by Alberta Agriculture, planting crops with the lower recommended fertilizer rate, such as peas, beans and alfalfa (Table 1), will reduce N2O emissions. In addition, F_{CR} is proportional to the product RN (Table 1) of ratio (R_{BG}) of below-ground residues dry matter to harvested yield and N content (N_{BG}) of below-ground residues of main crops in Equation (22). Therefore, plating crops with the smaller product RN, such as soybean (0.002), corn for grain (0.0028) and bean (0.004), will also reduce N_2O emissions. Table 2 also shows the fractions of F_{SN} and N_2O_{mm} from each municipality in Alberta, respectively. The maximum fraction of F_{SN} for all of Alberta was 0.0414 (Taber County), then 0.0405 (Vulcan County), and 0.0376 (Wheatland County). This order was the same as that of synthetic fertilizer mass inputs to the soils of the three counties (Table 3). The maximum fraction of N_2O_{mm} in the province of Alberta was 0.081 (Lethbridge County) followed by 0.051 (Taber County), and 0.041 (Vulcan County). This order was also the same as the order of populations of dairy cows and cattle cows in the three counties (Table 2).

4. Conclusions

Based on the 2011 agricultural data provided by Statistics Canada and Alberta Agricultural and Forestry, CH_4 and N_2O emissions from agricultural activities of 69 municipalities in Alberta were calculated using IPCC 2006 tire 1 and 2 methods. A basic pattern of emissions in Alberta was that CH_{4Tot} and N_2O_{Tot} increased from Northwestern to Southeastern municipalities. The total CH_4 and N_2O emissions of the entire province of Alberta agriculture in 2011 were 328 Gg CH_4 yr^{-1} and 23.5 Gg N_2O yr^{-1}, respectively. The southern Lethbridge municipality emitted the largest CH_4 and N_2O of all the municipalities (25.3 Gg CH_4 yr^{-1} (7.70% of total CH_4 in all of Alberta) and 1.26 Gg N_2O yr^{-1} (5.40% of total N_2O for all of Alberta), respectively, due to its largest cattle population (414,627 head), and larger synthetic fertilizer input (32,111 ton-N) and planted area (206,077 ha) among the 69 municipalities. The second large CH_4 and N_2O emission source was also located at the south: Taber County, which emitted 15.8 Gg CH_4 yr^{-1} (4.80% of total CH_4 for all of Alberta) and 1.14 Gg N_2O yr^{-1} (4.80% of total N_2O for all Alberta), respectively. The authors also developed a method for estimating synthetic fertilizer rate used in each crop from the total synthetic fertilizer mass of a municipality, in which the total synthetic fertilizer mass was correlated with the recommended fertilizer rate by Alberta Agriculture and Forestry, and planted area of each crop in a municipality. Using this method, the total synthetic fertilizer mass in 69 municipalities were reasonably distributed to each crop planted in all of these municipalities. This method provides a tool to accurately manage all fertilizer usage levels and to control the GHG output at a crop specific fertilizer rate.

The present method also will be expected to be applied to long-term data such as 20 years available from Statistics Canada and Alberta Agriculture and Forestry to observe changing trends of CH_4 and N_2O emitted from both animal and crop farms in the province of Alberta. Furthermore, according to the spatial pattern of CH_4 and N_2O emissions, animal populations, synthetic fertilizer applied to soils, and economic crops are main sources CH_4 and N_2O emissions from the Alberta agricultural sector. Policy makers can recommend a lower fertilizer rate as well as with the smaller product of R_{BG} and N_{BG} in the hot-spot counties, which can greatly reduce CH_4 and N_2O emissions. However, balances among various production factors, such as crop types, crop, milk and beef yields, fertilizer rates and greenhouse emissions should be systematically considered. Because Tier 1 cannot resolve spatial and temporal variation in soil and climate although it is simple, comparable and transparent, country-specific Tier 2 and Tier 3 should be developed because they are more accurate for emission calculation. In this regard, EFs from Tier 2 and Tier 3 can be a substitution for that from Tiers 1 in this framework. This can provide more detailed assessment of CH_4 and N_2O emissions using different agricultural management for policy makers.

Acknowledgements

The authors thank the financial support from Alberta Economic Development and Trade via Campus Alberta Innovation Program (CAIP) Research Chair (No. RCP-12-001-BCAIP) and the Statistics Canada and Alberta Agriculture and Forestry for their providing agricultural data. The authors would thank Mr. Jim Sellers for proofreading.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.06.270.

Nomenclature list

A	Planted area (ha)
a	A proportional constant (dimensionless)

CH_{4E}	Emissions from enteric fermentation (Gg CH_4 yr^{-1})
CH_{4M}	Emissions from manure management (Gg CH_4 yr^{-1})
D.M.	Dried matter (kg)
EF	Emissions factor (kg CH_4 $head^{-1}$ yr^{-1})
EF_1	Emission factor for N_2O emissions from N inputs (kg $N_2O{-}N$ (kg N input)$^{-1}$) (Table S1 cited from Table 11.1 of IPCC, 2006)
EF_3^m	Emission factor for direct N_2O emissions from m type of manure management system (kg $N_2O{-}N$ (kg N)$^{-1}$)
EF_{3PRP}	Emission factor for N_2O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals (kg $N_2O{-}N$ (kg N input)$^{-1}$) (Table S2 cited from Table 11.1 of IPCC, 2006)
EF_4	Emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (kg $N{-}N_2O$ (kg $NH_3{-}N$ + $NOx{-}N$ volatilized)$^{-1}$) (Table S3 cited from Table 11.3 of IPCC, 2006)
EF_5	Emission factor for N_2O emissions from nitrogen leaching and runoff (kg $N_2O{-}N$ (kg N leached and runoff)$^{-1}$) (Table S3)
ex^k	Total fertilizer expenses (C$) in *k* municipality
F_{CR}	Annual mass of N in crop residues returned to soils (kg N yr^{-1})
F_{fSN}^k	Total fertilizer mass in k municipality (kg-fertilizer)
$F_{fSN}^{k,j}$	j type fertilizer mass used (kg-fertilizer)
F_{ON}	Annual mass of livestock manure, and other organic N additions applied to soils (kg N yr^{-1})
F_{ON}^k	Total organic fertilizer in *k* municipality (kg-N $head^{-1}$ yr^{-1})
F_{PRP}	Annual mass of urine and dung N deposited by grazing animals on pasture, range and paddock (kg N yr^{-1})
$Frac_{GASF}$	Fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx (kg N volatilized (kg of N applied)$^{-1}$ (Table S3 cited from Table 11.3 of IPCC, 2006) (dimensionless)
$Frac_{GASM}$	Fraction of applied organic N fertilizer materials (F_{ON}) and of urine and dung N deposited by grazing animals (F_{PRP}) that volatilizes as NH_3 and NOx (kg N volatilized (kg of N applied or deposited)$^{-1}$) (Table S3 cited from Table 11.3 of IPCC, 2006) (dimensionless)
$Frac_{GasMS}$	Percentage of managed manure nitrogen for *i* type of livestock that volatilizes as NH_3 and NOx in the *m* type of manure management system (%)
$Frac_{leachMS}$	Percentage of managed manure nitrogen losses for *i* type of livestock due to runoff and leaching during solid and liquid storage of manure (Table S3) (%)
$F_{racRenew}$	Fraction of total crop area under crop (dimensionless)
F_{SN}	Annual mass of synthetic fertilizer applied to soils (kg N yr^{-1})
F_{SN}^k	Sum of nitrogen contents in three fertilizers in *k* municipality (kg-N)
$F\text{-}N_{SN}$	Fertilizer mass as nitrogen as base (kg-N)
$fp^{k,j}$	j type fertilizer price per kg (C$ (kg fertilizer)$^{-1}$)
$MS^{i,m}$	Fraction of annual nitrogen excretion for i type of livestock that is managed in *m* type of manure management system in *k* municipality (Table S3)
Nex	Manure rate produced by *i* type of livestock (kg-N $head^{-1}$ yr^{-1})
N_{BG}	N content of below-ground residues (kg N (kg D.M.)$^{-1}$
$N_2O{-}N_{Ninputs}$	Annual direct $N_2O{-}N$ emitted from N applied soils (kg $N_2O{-}N$ yr^{-1})
$N_2O{-}N_{PRP}$	Annual direct $N_2O{-}N$ emitted from grazed soils inputted by animal urine and dung (kg $N_2O{-}N$ yr^{-1})
$N_2O_{ATD}{-}N$	Annual amount of $N_2O{-}N$ produced from atmospheric deposition of N volatilized from managed soils (kg N_2O yr^{-1})
$N_2O_D{-}N$	Annual direct $N_2O{-}N$ emitted from managed soils (kg $N_2O{-}N$ yr^{-1})
N_2O_{Gmm}	Indirect N_2O emissions due to volatilization of N from manure management in *k* municipality (kg N_2O yr^{-1})
N_2O_{Lmm}	Indirect N_2O emissions due to leaching and runoff from manure management in *k* municipality (kg N_2O yr^{-1})
N_2O_{mm}	Direct N_2O emissions from manure management in *k* municipality (kg N_2O yr^{-1})
N_{rate}^i	Default N excretion rate (kg N (1000 kg head mass)$^{-1}$ day^{-1}
RN	Product of ratio (*RBG*) of below-ground residues dry matter to harvested yield and N content (N_{BG}) of below-ground residues of main crops (dimensionless)
R_{ac}	Actual fertilizer rate used (kg-N ha^{-1})
R_{BG}	Ratio of below-ground residues dry matter to harvested yield (kg D.M. (kg D.M)$^{-1}$)
R_r^l	Recommended fertilizer rate of l type of crop proposed by Alberta Agriculture (dimensionless)
r^j	Fraction of *j* type of fertilizer in three fertilizers (dimensionless)
$r^{k,l}$	Fraction of product of fertilizer rate used and planted area for l type of crop in k municipality in sum of above products
P	Population of animal (head)
TAM^i	Typical animal mass for *i* type of livestock (kg $head^{-1}$)
10^6	A unit conversion factor (kg Gg^{-1})
44/28	Conversion of $N_2O\text{-}N_{mm}$ emissions to N_2O_{mm} emissions

Superscripts

i	Animal type
j	Type of fertilizer price
k	Municipality
l	Crop type
m	Index of manure management system

Subscripts

CPP	Cattle, poultry and pigs
SO	Sheep and other animals

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