Agricultural Ammonia Indicator

Agri-Environmental Indicators Report

The Environmental Sustainability of Canadian Agriculture

Census Year 2021

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Agricultural Ammonia Indicator
Agri-Environmental Indicators Report, Census Year 2021

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Summary

Ammonia (NH_3) is a basic, reactive and potentially toxic gas composed of nitrogen (N) and hydrogen (H) that can nourish plants but may also have negative impacts on the environment and human health. In Canada, agriculture is responsible for about 93% of the total anthropogenic NH_3 emissions to the atmosphere (Environment and Climate Change Canada, 2021). The highest NH3 emissions occur in regions with concentrated livestock production, especially in the southern parts of Quebec, Ontario and Manitoba, parts of Alberta and the lower Fraser Valley of British Columbia. Ammonia is released from manures mainly after breakdown of excreted urea (cattle and pigs) or uric acid (poultry). Ammonia emissions also come from N fertilizers containing ammonia, ammonium or urea. When present at high concentrations in enclosed spaces such as poultry barns, ample ventilation is needed so that the emitted NH_3 does not become an irritant, or even toxic, to humans and animals.

The 'Ammonia Emissions from Agriculture' agri-environmental indicator has been developed to estimate Canadian agricultural NH_3 emissions based on spatial and temporal information about agricultural production, management practices and emission factors associated with agricultural practices. The Indicator assesses the broad-scale state and trend of the sectoral NH_3 emission levels nation-wide and spatially, across the Canadian agricultural landscape and for each Soil Landscape of Canada (SLC) polygon and each month of the year.

In 2021, national NH_3 emissions from all agricultural sources summed to 403 kilotones (kt) compared to 325 kt in 1981, with emissions from fertilizers then accounting for only 17% of the total agricultural emissions. Since 1981, emissions from fertilizer application (emissions during manufacture are not included in this metric) have increased 2.9-fold (from 54 kt NH_3 in 1981, to 156 kt NH_3 in 2021, now 39% of total) mainly due to increases in N fertilizer use and a switch to urea based sources, whereas livestock emissions have been decreasing (by 51 kt), particularly since 2006. The emissions reflect an overall trend towards fewer livestock and increased area under crops, necessitating greater fertilizer use.

Most ammonia emissions occur in spring due to manure and fertilizer application activity, moderate amounts in summer and fall, whereas little is emitted in winter when there is little spreading and low emissions from relatively cold manure storages and animal housing. The temporal and spatial distribution of the inventory is generally supported by recent earth observations. There is concern that ammonia reacting with acid gases in the atmosphere results in fine particulates that are known to be detrimental to human health and may have further social effects by impeding visibility and contaminating pristine natural ecosystems, as particles, aerosols or gas. Modelling

shows that most particulate matter (PM) formation occurs in southern Quebec and Ontario, as well as southwestern British Columbia. The 332 kt NH_3-N loss as ammonia into the atmosphere annually is equivalent to 11% of N current fertilizer consumption in Canada with a value of roughly $400-800 million Canadian dollars. Emitted ammonia, while reducing on-farm nitrous oxide (N_2O) emissions, gives rise to secondary emissions when it is deposited on soils that are counted in greenhouse gas emissions inventories, and are about 0.5 million tonnes of carbon dioxide equivalent (Mt CO_2e). Minimizing nitrogen loss as ammonia is desirable, as loss reduces the efficiency of fertilizer and manure, requiring increased inputs and expenditures to compensate.

The issue and why it matters

Ammonia is both a plant nutrient and a by-product of protein digestion and degradation in animals, especially protein consumed in excess of assimilation. Excess protein-N is excreted from livestock in the form of urea in mammalian urine and uric acid in avian manure and in more complex organic molecules in faeces. Ammonia is also released slowly from the breakdown of organic N compounds in manure, soil organic matter and crop residue and is emitted directly from plant leaves. Ammonia is also released from most N fertilizers which contain urea and ammonia- or ammonium-N but not those containing only nitrate-N. Ammonia emissions from agriculture sources, referred to as fugitive, are inherent to all plant and animal life and occur in natural, as well as managed, landscapes. The release of ammonia generally precedes other N losses in agricultural systems such as nitrous oxide (N_2O) and nitrate (NO_3^-), meaning the other losses are net of ammonia emissions and are difficult to compute without good estimates of ammonia emissions. As can be seen below and in other chapters in this volume, the loss of N by various pathways from Canadian agriculture is significant relative to fertilizer inputs and other environmental losses. Although ammonia is not a greenhouse gas, it is assumed that in Canada 0.5-1.4% of evolved ammonia is emitted as N_2O after deposition, and is referred to as indirect or secondary N_2O emissions.

Ammonia is water soluble and readily reacts with acid gases, notably nitrogen oxides (NOx) and sulphur oxides (SO_x), as well as chloride (Cl^-) and organic acids in the atmosphere, generating ammonium- (NH_4^+) based compounds in the form of fine respirable particulates (referred to as secondary particulates) less than 2.5 micrometres in diameter ($PM_{2.5}$). These fine particulates can contribute to smog and are detrimental to human health (Deutsch et al., 2008; Domingo et al., 2021). It is due to this health hazard that NH_3 is designated a Criteria Air Contaminant in Canada (https://www.canada.ca/en/environment-climate-change/services/air-pollution/pollutants/common-contaminants.html). While the secondary $PM_{2.5}$ cannot be fully attributed to agricultural NH_3 emissions, the agricultural sector in Canada contributes the majority (93%) of the total anthropogenic NH_3 gas emissions (Environment and Climate Change Canada, 2019) so there would be much less $PM_{2.5}$ without agricultural emissions. NH_4^+ based PM form particularly in areas that feature abundant livestock production and/or intensive fertilizer use, which are located near urban centres or industrial sites emitting large amounts of acidic NO_x and SO_x (Erisman and Schaap, 2004). The haze that forms in southern Ontario and in the Lower Fraser Valley of British Columbia contains NH_3-based particles; Barthelmie and Pryor (1998) attributed the extensive “grey smog” events that occur mainly in late summer in the Lower Fraser Valley to livestock-related NH_3 emissions reacting with the acid gases from vehicles (Figure 1). These events reduce visibility and likely have a negative economic impact on tourism and film sectors (Cecato, 2019; McNeill and Roberge, 2000).

Figure 1: Mountains in British Columbia's Lower Fraser Valley shrouded in a haze caused by secondary PM during a clear day in the late summer, August 12, 2012

(left photo), and the same vista on a clear day in mid-winter, February 2, 2013 (right photo). The haze-inducing particulate matter, composed primarily of ammonium nitrate, results from chemical reactions between ammonia emitted mainly from agricultural sources (such as poultry housing, as visible at the bottom left of both photos) and nitrogen oxides emitted by vehicles. From Bittman et al. (2014).

Atmospheric gaseous NH_3 is very water soluble and adsorptive and has a low emission height from agricultural sources and hence is readily deposited onto rough surfaces (referred to as dry deposition) such as vegetation and soil within a few hundred meters of sources, especially livestock operations and land spreading (Asman et al., 1998). In contrast, atmospheric NH_4^+ is bound in particles or aerosols and may be transported by air current up to hundreds of kilometers and deposited in natural areas that are vulnerable to N enrichment, such as alpine vegetation, oligotrophic peat bogs or calcium-depleted soils or even pristine mountain lakes (Baron et al., 2011). There is modelling evidence that ammonia emitted in the Midwest USA affects air quality in southern Ontario, and NH_3 emitted in southern Ontario affects local remote ecosystems located downwind in other parts of Ontario and in Quebec (Makar et al., 2009; Zbieranowski and Aherne, 2013).

Wet deposition of both reduced ammonium PM or aerosols and oxidized (NO_x) gases is monitored in the USA and Canadian border regions by the National Atmospheric Deposition Program (NADP). The European Union (EU), to protect biodiversity, has set National Emission Ceilings (NEC) to limit atmospheric ammonia emissions by each member state, but there are no ammonia emission regulations in Canada or the USA. Because ammonia/ammonium moves freely across international boundaries, the countries of the United Nations Economic Commission for Europe (UNECE), which include Canada and the USA, have listed ammonia in the Conventional for Long-Range Transboundary Air Pollution (CLRTAP) and the associated Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. Canada has ratified the revised protocol, which was adopted in 2012, and has committed to annually report emissions from all agricultural and non-agricultural sources. To assist countries to implement abatement measures, the UNECE has published a detailed Guidance Document for abating ammonia emissions in the context of other N species (Bittman et al., 2014), as well as a basic Framework Code of Agricultural Practices which is a default document for all parties without their own Code. Ammonia losses are also described in the context of all N species (Misselbrook et al., 2022).

Atmospheric ammonia emissions increase greatly from winter to spring in accordance with increased temperatures and farming activities, notably land spreading of fertilizer and manure and animal activity, due to calving for example (Bittman et al., 2023). Seasonality of atmospheric ammonia is important as it affects risk of human exposure to $PM_{2.5}$. Also, there are large seasonal variations in air flow patterns, temperature and solar radiation which affect atmospheric chemistry and transport, with implications for vulnerable natural vegetation, water and soil. Ammonia emissions also vary diurnally due to changes in light, temperature, farm activity and atmospheric chemistry.

In soils that are below a pH of 7, due to a surplus of hydrogen (H^+) atoms, NH_x is mostly in the ammonium form NH_4^+ where it can be adsorbed to clay, absorbed by plants and transformed by microbes into several other environmentally important reactive forms of nitrogen (Nr) and immobilized into organic molecules and clay matrices. The most abundant Nr in unsaturated soils is usually NO_3^- which results mostly from NH_4^+ oxidation (called nitrification) and which releases hydrogen atoms and acidifies soils, so that wet deposition of ammonia and ammonium is now a pre-eminent acidifier of natural soils (sometimes referred to as acid rain). The NO_3^- is easily absorbed by plants to support growth or by microbes which immobilize or chemically reduce (denitrify) the NO_3^- to non-reactive N_2 gas, which is returned to the atmosphere where it is the dominant gas. Both the aerobic nitrification and anaerobic denitrification processes, which can happen at once in a soil with moderate water content due to variable microsites, give rise to the potent greenhouse gas N_2O. It is important to note that between 0.5 and 1.4% of fugitive ammonia emissions in Canada is thought to result in N_2O, regardless of landscape. The sequence of transformations reactive forms of N undergo in the environment, referred to as the nitrogen cascade (Galloway et al., 2003), illustrate how ammonia emissions can contribute to various environmental consequences (Figure 2).

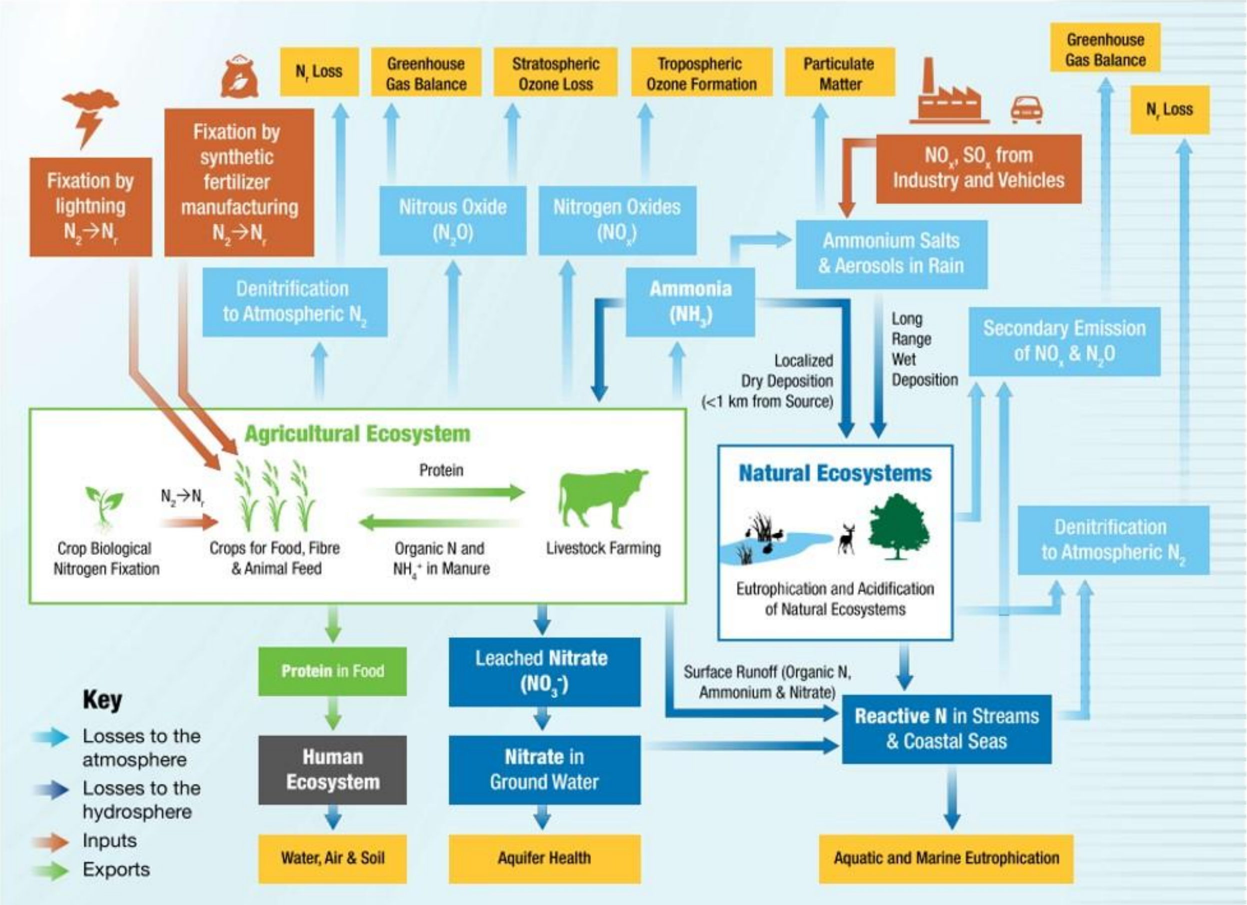


Figure 2. Simplified nitrogen cascade (Galloway et al., 2003), showing the fate of reactive N used in agriculture (adapted from Sutton et al. 2022).

For farmers, the loss of NH_3 from agriculture represents the loss of a critical nutrient which must be replaced by expensive mineral fertilizer inputs. Canada-wide, the loss of 403,000 tonnes (t) of NH_3 (332,000 t of N) from farms in 2021 is equivalent to approximately 11% of all the fertilizer N shipped to farms and other users that year, which translates into an economic loss value of well over $400-800 million CAD (based on 2020 and 2022 prices for urea fertilizer, respectively). Replacement of lost NH_3-N not only has a monetary cost for the producer, it has broader economic and environmental implications associated with the production and transport of N fertilizer which consumes large amounts of non-renewable, geo-politically important natural gas (methane) and is therefore a substantial contributor of agricultural energy consumption in Canada, but which is reported as industrial rather than agricultural GHG emissions.

The Ammonia Emissions from Agriculture Indicator

The ‘Ammonia Emissions from Agriculture’ Indicator estimates the annual emissions of NH_3 to the atmosphere from livestock production and fertilizer applications, per hectare of land, in each of 3,400 agricultural Soil Landscape of Canada (SLC) polygons. This approach allows the NH_3 indicator to be compatible with other nitrogen indicators such as the Residual Soil Nitrogen and Nitrous Oxide component the Greenhouse Gas Indicator, except that NH_3-N units are used by the other indicators (and are 17% smaller than NH_3). Unlike the other environmental indicators, the NH_3 indicator computes emissions on a monthly basis since these data are needed to interpret the environmental fate and impact of NH_3 and to suggest most effective abatement measures (also known as Beneficial Management Practices, or BMPs).

The indicator is generated with a series of computational models that use data from several sources: 1. Farm activity - farm practices in 12 Ecoregions of Canada obtained mostly from special farm surveys focusing on ammonia emissions, and supplemented with expert opinion to fill survey gaps; 2. Animal numbers and crop areas from the Census of Agriculture and additional annual survey data and N fertilizer shipments from Statistics Canada; 3. Canadian emission factors based on published (e.g., Søgaard et al. (2002)) and unpublished Canadian and other sources adapted to Canadian farm practices and conditions; 4. Canadian-specific emission fractions determined, for example, for each stage of the ‘manure train’ using emission factors adapted to each farm activity. Figure 3 shows the step-wise flow of manure from excretion in livestock housing, to storage in manure management systems, to final application of the manure on agricultural land, for each of the primary farm animal types; and from each form of ammonia relevant fertilizers as affected by their application timing and practices. There is still limited manure processing in Canada, so emission from processing has not be included in the model. Specialized models are used for broilers, layers, turkeys, swine, dairy cattle, beef cattle and fertilizers and to accommodate their particular production system and attributes in each Ecoregion across Canada. Sub-models are used for subsectors such as, in the case of the dairy sector, calves, heifers, dry cows and lactating cows. The livestock models have several common attributes (reported in

Sheppard et al. (2009) and other peer reviewed publications listed below in the publications section):

- They are based on total ammoniacal nitrogen (TAN) in excreted manure, including urine and uric acid, estimated from feeding practices.
- The amount of N excreted is assumed to be equal to the amount of protein-N consumed by the animal, minus the protein-N retained in animal tissues and exported products (eggs and milk). TAN is a literature-based fraction of total excreted N supported where possible by Canadian data.
- For confined animals, the models track the transfer of excreted TAN and the loss of NH_3 from successive stages of housing (including open pens), storage and land spreading. Losses from excretion, mainly urine, deposited by grazing animals are considered to result from a single stage.
- Canadian feeding and production practices for all sectors are analyzed using several NH_3 focused farmer surveys conducted by Statistics Canada and others which have been published in peer reviewed journals (listed below).
- Wherever possible, mathematical functions from the literature that relate emissions to farm practices and environmental factors are used to calculate emission fractions for each of 12 Ecoregions, because these mathematical functions typically summarize a large amount of data and allow interpolation to specific conditions. Canadian emission rates are adjusted based on regional monthly average temperatures and the probability of precipitation immediately following land spreading of manure.
- Animal numbers are taken from the Census of Agriculture and annual surveys from Statistics Canada census districts and are ascribed to SLC polygons according to standardized methods.

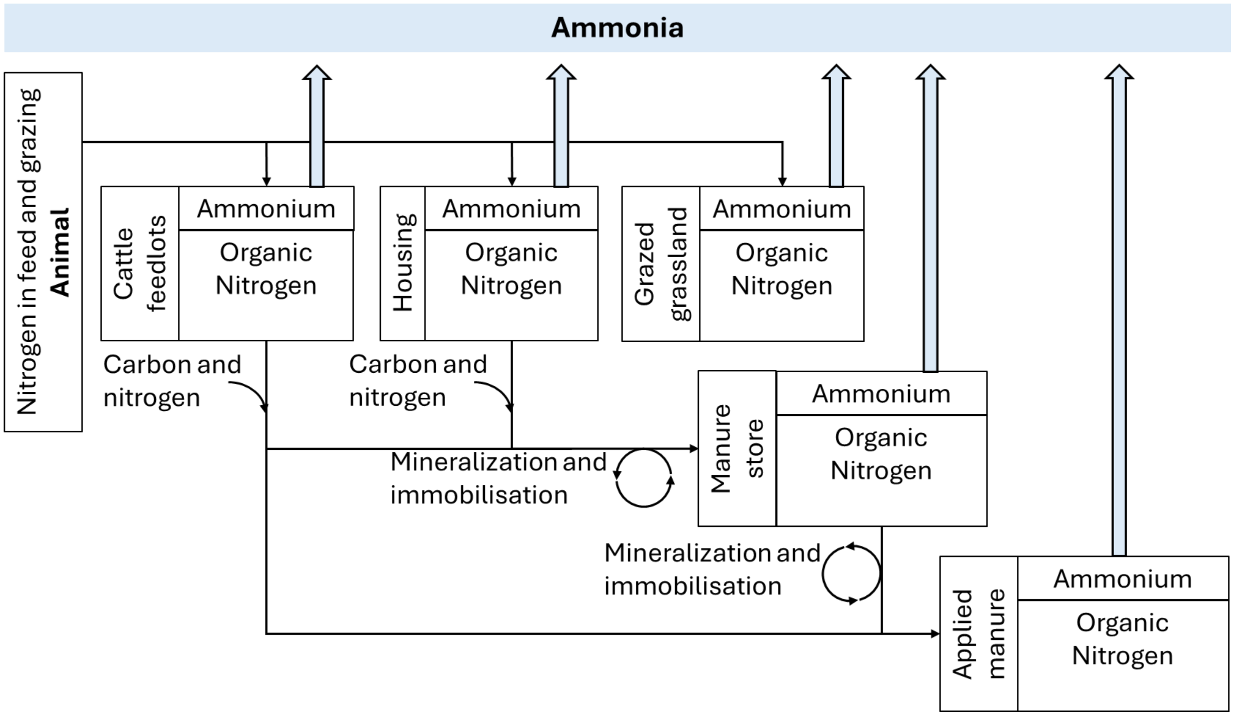


Figure 3. Manure train, the step-wise movement of manure from excretion in livestock housing, to storage in manure management systems, to final application of the manure on agricultural land with ammonia lost at each stage (blue arrows). Losses of ammonia from grazed grasslands are considered to result from a single stage.

The fertilizer emission model (Sheppard et al., 2010) computes the NH_3 emissions per area of land for 35 crop types. Emissions from fertilizer use are estimated as the amount of different forms of nitrogen fertilizer applied per hectare, multiplied by the fractions of applied N that are emitted as NH_3, based on fertilizer properties and condition-modified monthly application practices, including rates. Crop areas are taken from annual surveys conducted by Statistics Canada and are distributed to SLC polygons according to standardized methods.

The model and model documentation are maintained by the Sustainability Metrics Division of Agriculture and Agri-Food Canada, Science and Technology Branch. International reporting is conducted by Environment and Climate Change Canada.

Limitations

The indicator has been calculated for the Census years from 1981 to 2021, based on detailed information about livestock feeding, housing and manure management, as well as fertilizer application practices compiled in 2006 (except beef which is adapted to a

2012 survey). It has been necessary to assume farm practices were similar to 2006 for the entire 40-year period, due to the lack of alternative data, and therefore changes in farm practices that affect emissions (such as injection of liquid manure and winter grazing of beef cattle) cannot be quantified over that entire time frame. Going forward, with a strong database of on-farm management practices from 2006 and with periodic updates, the ammonia indicator could be made responsive to evolving farm management practices, including new abatement measures that result in changes in emissions. These updates will also improve estimates of residual soil nitrogen (RSN) in fall and total N_2O emissions (Yang et al., 2023).

The indicator data have some inherent uncertainties. However, the overall estimates are influenced most strongly by livestock and fertilizer statistics (Sheppard et al., 2010; Sheppard et al., 2007), which are very reliable in Canada, and by N excretion rates, which are fairly well understood for most livestock types based on feeding practices. The model-adjusted excretion rates account for protein in feeds reported in the farm surveys. Farm practice information are based on the detailed results of farm activity surveys focusing on ammonia, which are carefully stratified by animal type and Ecoregion and reflects the distribution of farm sizes appropriately. Where Canadian emission factors were not available, the most suitable emission factor data from Europe and the United States were chosen and adjusted to reflect Canadian conditions and practices. Emission fractions were computed in the model as emission factors prorated to the ensemble of Canadian farm practices and conditions for each sector and ecoregion. Uncertainty of emission fractions is mitigated by the large number of generally independent computations in the model, which suggests statistically diminishing error for the total emissions estimate. Because emissions from beef cattle are especially influential on national estimates, and because of a substantive change in farm practices (winter grazing), beef practices were re-surveyed in 2011 in collaboration with the University of Manitoba (Sheppard et al., 2015). As in other national inventories, local deposition is not removed from the emission calculations due to insufficient data but is assumed to be up to 5-19% (Hao et al., 2006; Seeton, 2016) with emission height and local surfaces as factors. Note that an uncertainty level of 20% was estimated for the United Kingdom’s inventory of NH_3 emissions from agriculture which has a similar structure (Webb et al., 2009).

This indicator requires careful interpretation because the atmospheric transport and chemical reactions involving NH_3 are affected by the weather, and emission rates vary markedly throughout the year (Makar et al., 2009; Philip et al., 2014; Shephard et al., 2020; Vet et al., 2010). Furthermore, emission may have a much greater impact in some regions than others due to human or vegetation exposure and vulnerability, and the impact of ammonia-based $PM_{2.5}$ may occur at a considerable distance from the source depending on the prevailing winds. Averaging emissions over longer time periods is a limitation with respect to the role of NH_3 emissions in the formation of smog. Smog events can last hours or days, depending on whether other atmospheric pollutants able to react with NH_4^+ are present and depending on atmospheric conditions, notably wind, temperature and sunlight (Chu, 2004). Although monthly averaging of NH_3 emissions is not ideal for modelling these processes, monthly averages are a significant improvement over annual averages, given the large monthly variations in emissions.

Results and interpretation

In Canada, agriculture contributes about 93% of the total anthropogenic NH_3 gas emissions to the atmosphere (Environment and Climate Change Canada, 2019). Total NH_3 emissions increased from about 325 to 403 kt between 1981 to 2021 while other critical air contaminants (CAC) in Canada declined (https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/air-pollutant-emissions.html). Emissions from livestock accounted for 83% of total agricultural NH_3 emissions in 1981 and for about 77% between 1986 and 2006, before declining markedly to 70% of total emissions by 2011 and to 61% by 2021 (Figure 4). Throughout this period, emissions from N fertilizer use steadily increased, primarily in the Prairie Provinces (Figure 5 – lower panel). Livestock emissions decreased by 13% from 2006 to 2011 as a direct result of the decline in the beef cattle population due to occurrences of Bovine Spongiform Encephalopathy (BSE), with the largest declines occurring in the Prairie Provinces and especially Alberta where the Canadian beef industry is most concentrated (Figure 5 – upper panel). Other factors include the loss of ~2 million swine during this period and the gradual decline in dairy numbers due to increasing per-cow milk production, which predominantly impacts emissions in Manitoba and Eastern Canada. The beef sector accounted for 41% of emissions in 2006 compared to only 30% in 2021 (Figure 6). In 2021, emissions from fertilizers accounted for 39% of the total, surpassing beef, an increase from 22% in 2006. This reflects an overall trend towards increased area of arable crops (replacing summerfallow and perennial forages) and increased per hectare fertilizer application rates (due in part to more canola and better prices) and fewer livestock, trends that can be seen in Figure 5.

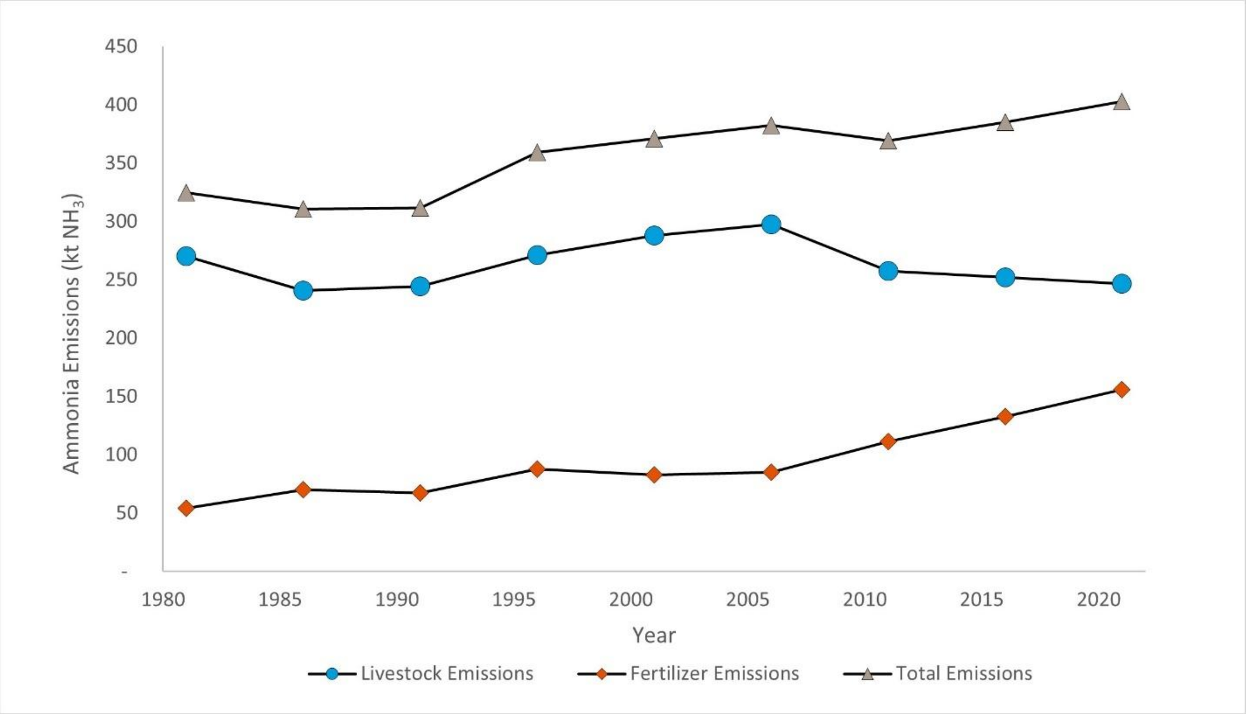
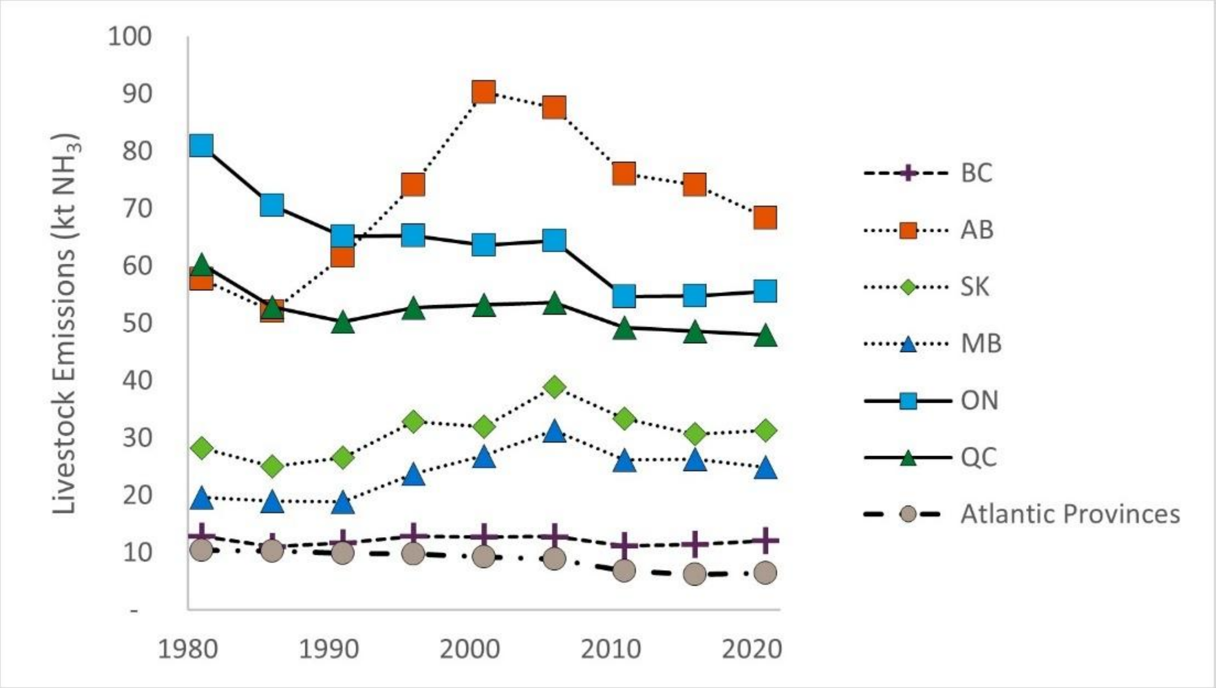


Figure 4. Annual ammonia emissions from animal production and fertilizer application in Canada from 1981-2021.



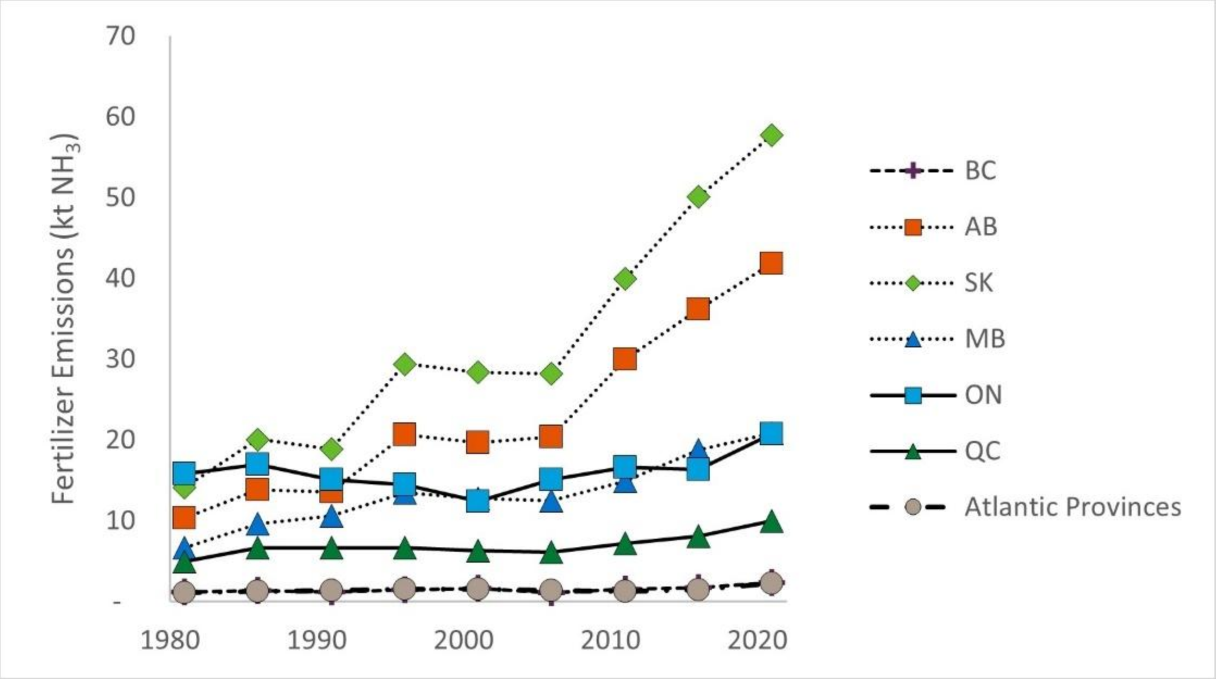


Figure 5. Annual ammonia emissions from animal production (top) and fertilizer application (bottom) in Canadian provinces from 1981-2021. The Atlantic Provinces include New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland and Labrador.

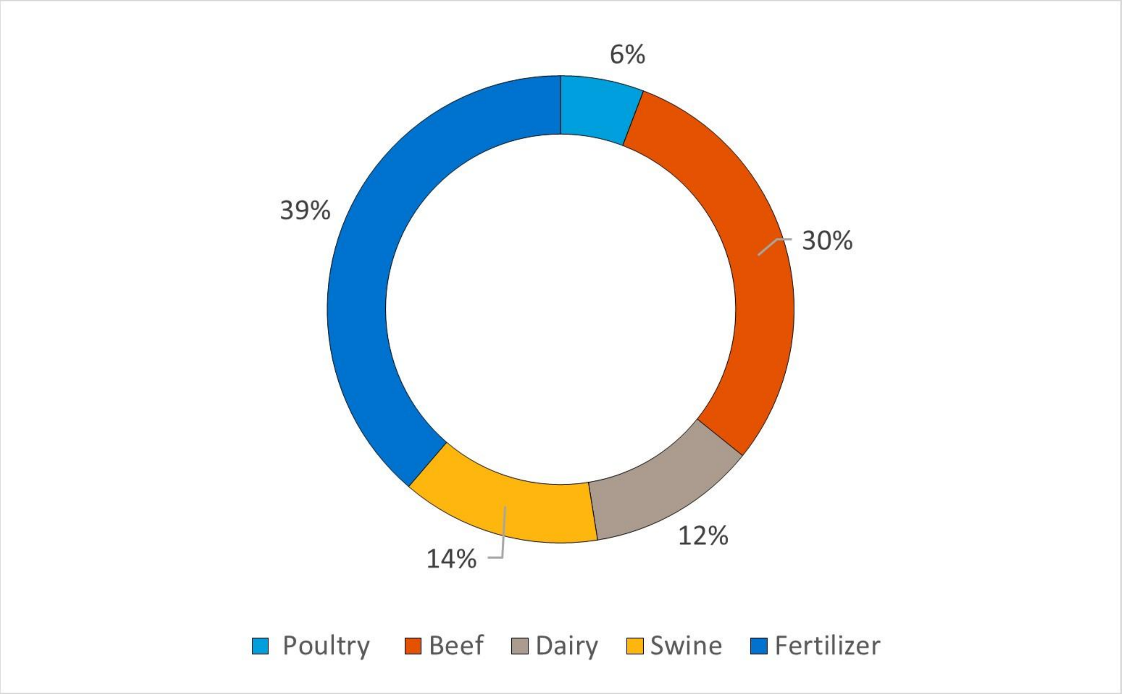
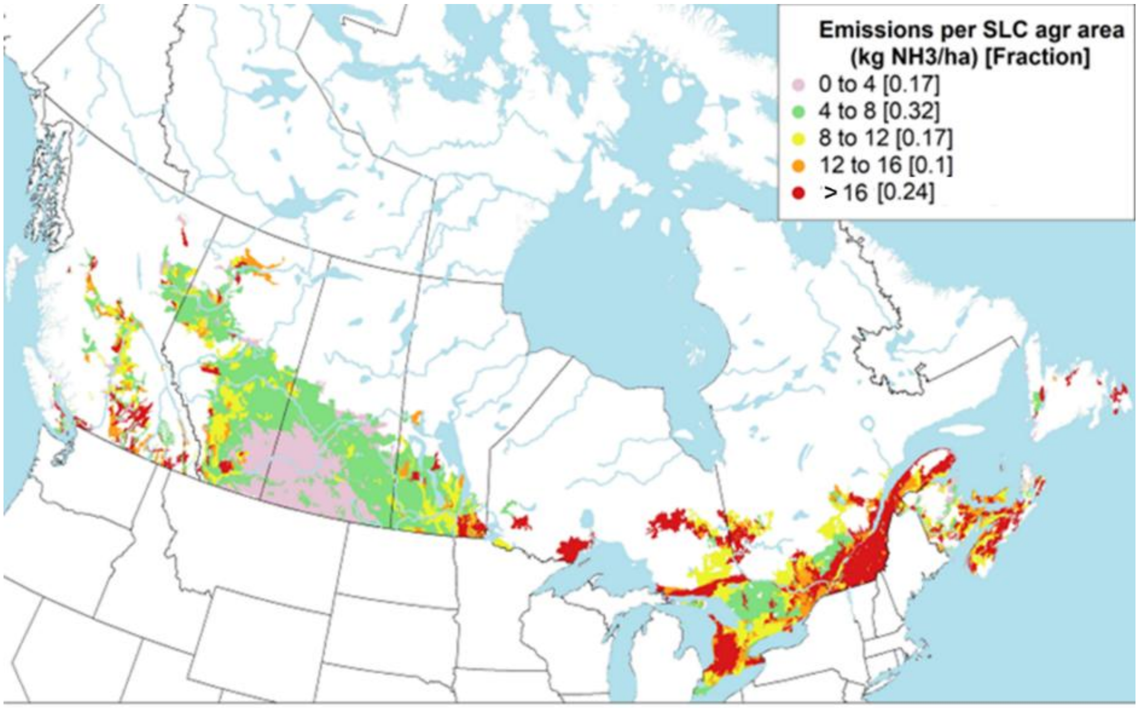


Figure 6. Percentage of agricultural ammonia emissions in 2021, by sector.

Total (livestock + fertilizer) NH_3 emissions expressed per hectare of agricultural land for 2021 are mapped at the SLC scale in Figure 7, and are shown separately for fertilizer and livestock NH_3 emissions in Figure 8 and Figure 9, respectively. Figure 8 illustrates a relatively even distribution of fertilizer emissions across the Canadian landscape, therefore the hot spot regions depicted in Figure 7 reflect mostly livestock emissions (Figure 9).

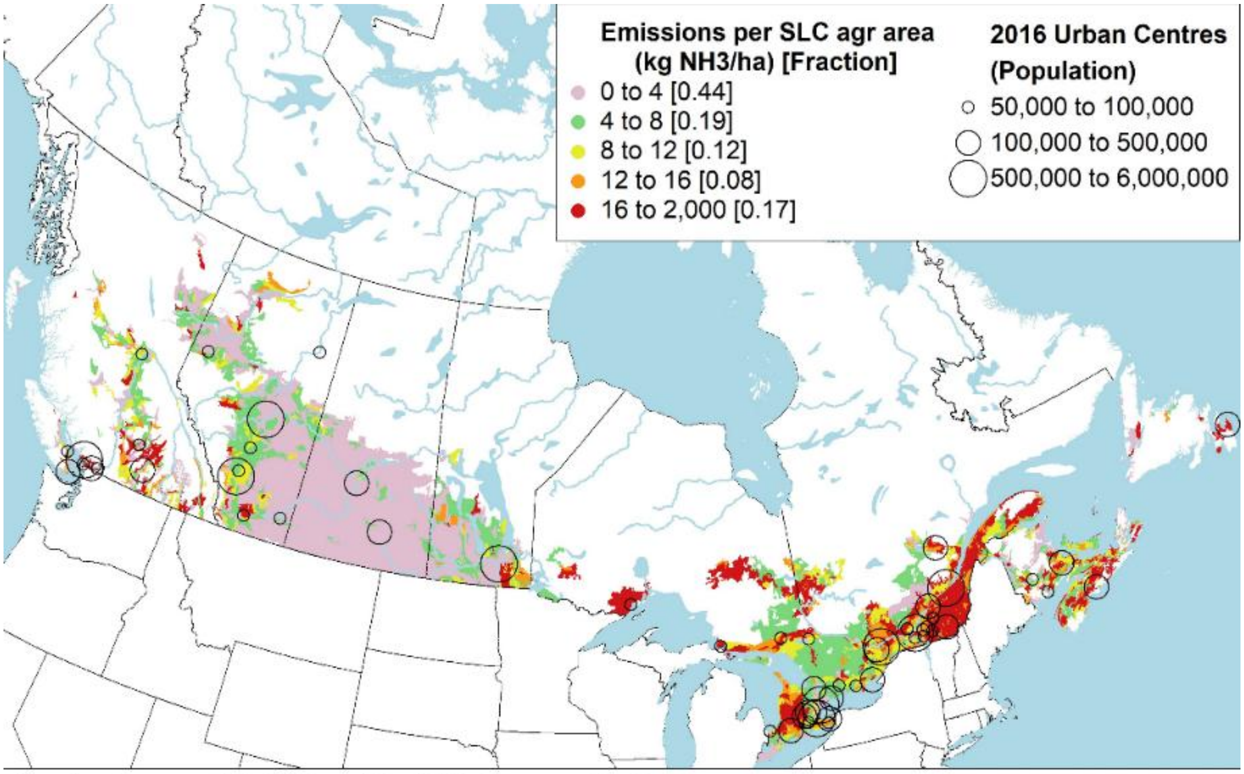


The coloured areas are agricultural SLCs, consisting of 3399 polygons across Canada.
The colours depict the output from TOTAL, per hectare of agriculture land (CROPLND + SUMMRF + IMPAST + UNIMPST).

Figure 7. Ammonia emissions from livestock plus fertilizer in 2021.

The map shows emissions averaged across agricultural land area in that SLC (depicted by colours). The values in square brackets in the legend indicate the fraction of the total SLCs in the associated bin.

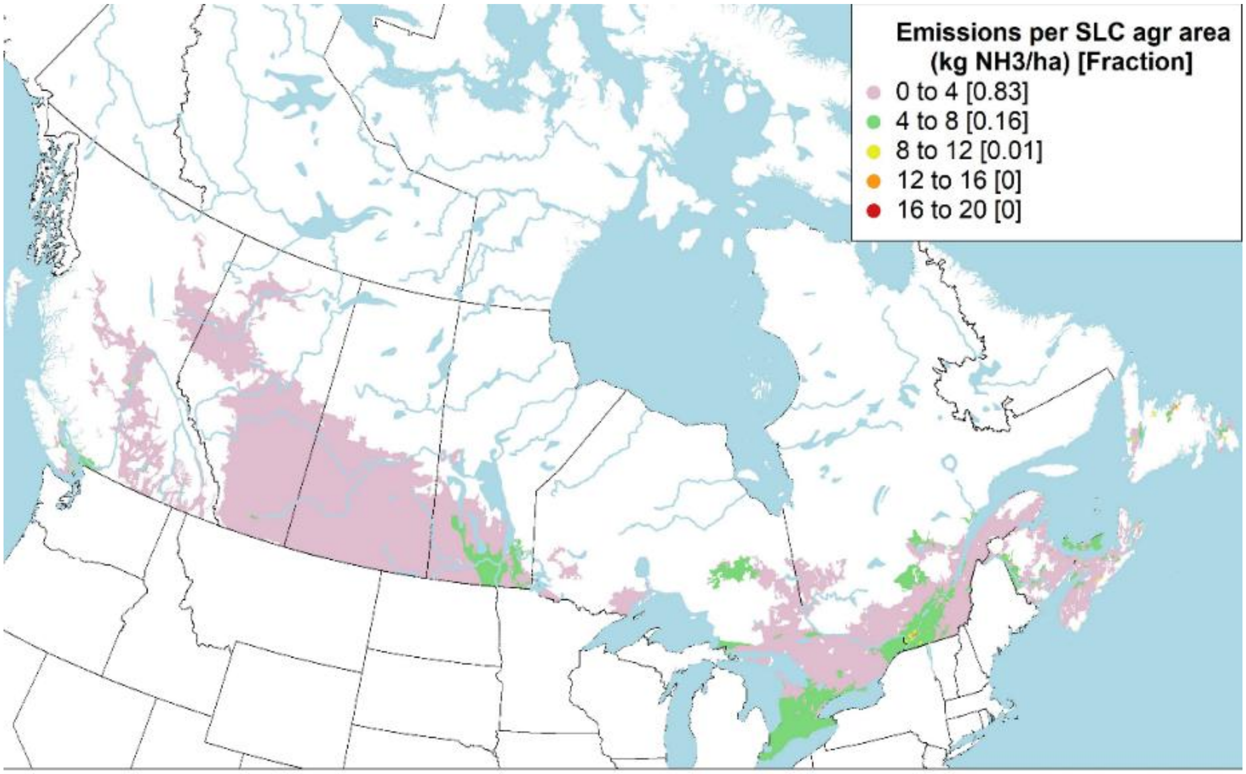
The notable lack of intense emission areas in SK compared to AB and MB is due to the dominance of thinly distributed fertilizers and low-density cow-calf operations in SK, which tends to result in a low spatial intensity of emissions. The use of fertilizer results in a widespread but relatively low NH_3 emission rate per land area, particularly in Western Canada, owing to the extensive areas of semi-arid cropland receiving relatively low (market driven) application rates; also low emission application techniques (especially side-banded, 5-centimetre deep injection) are widely used for spring grain crops. Because of more widespread application of fertilizer by injection methods, emissions of NH_3 from fertilizer applied to cropland accounted for about 4% of applied N in Saskatchewan compared to about 7% in Ontario, where injection is less common due to different cropping systems (more N is applied to winter wheat and forages where injection of N is less practical). The predominant fertilizer forms, across Canada, are potentially high emitters containing urea or ammonia. Thus, ammonia emissions intensity at the SLC scale is primarily driven by livestock concentration, which are greatest in the Lake Ontario-St. Lawrence River corridor in ON and QC (pigs and dairy), in the Lower Fraser Valley in BC (dairy and poultry), southern AB (beef feedlots) and southeastern MB (pigs); high values in the Atlantic provinces are associated with limited amounts of agricultural land associated with livestock Figure 10.



The coloured areas are agricultural SLCs, consisting of 3399 polygons across Canada.
The colours depict the output from TOTAL, per hectare of agriculture land (CROPLND + SUMMRF + IMPAST + UNIMPST).

Figure 8. Ammonia emissions from fertilizer in 2021.

The maps show emissions averaged across agricultural land area in that SLC (depicted by colours). The values in square brackets in the legend indicate the fraction of total SLCs in the associated bin.



The coloured areas are agricultural SLCs, consisting of 3399 polygons across Canada.
The colours depict the output from TOTAL, per hectare of agriculture land (CROPLND + SUMMRF + IMPAST + UNIMPST).

Figure 9. Ammonia emissions from livestock in 2021.

The maps show emissions averaged across agricultural land area in that SLC (depicted by colours). The values in square brackets in the legend indicate the fraction of total SLCs in the associated bin. The black circles represent urban population centres.

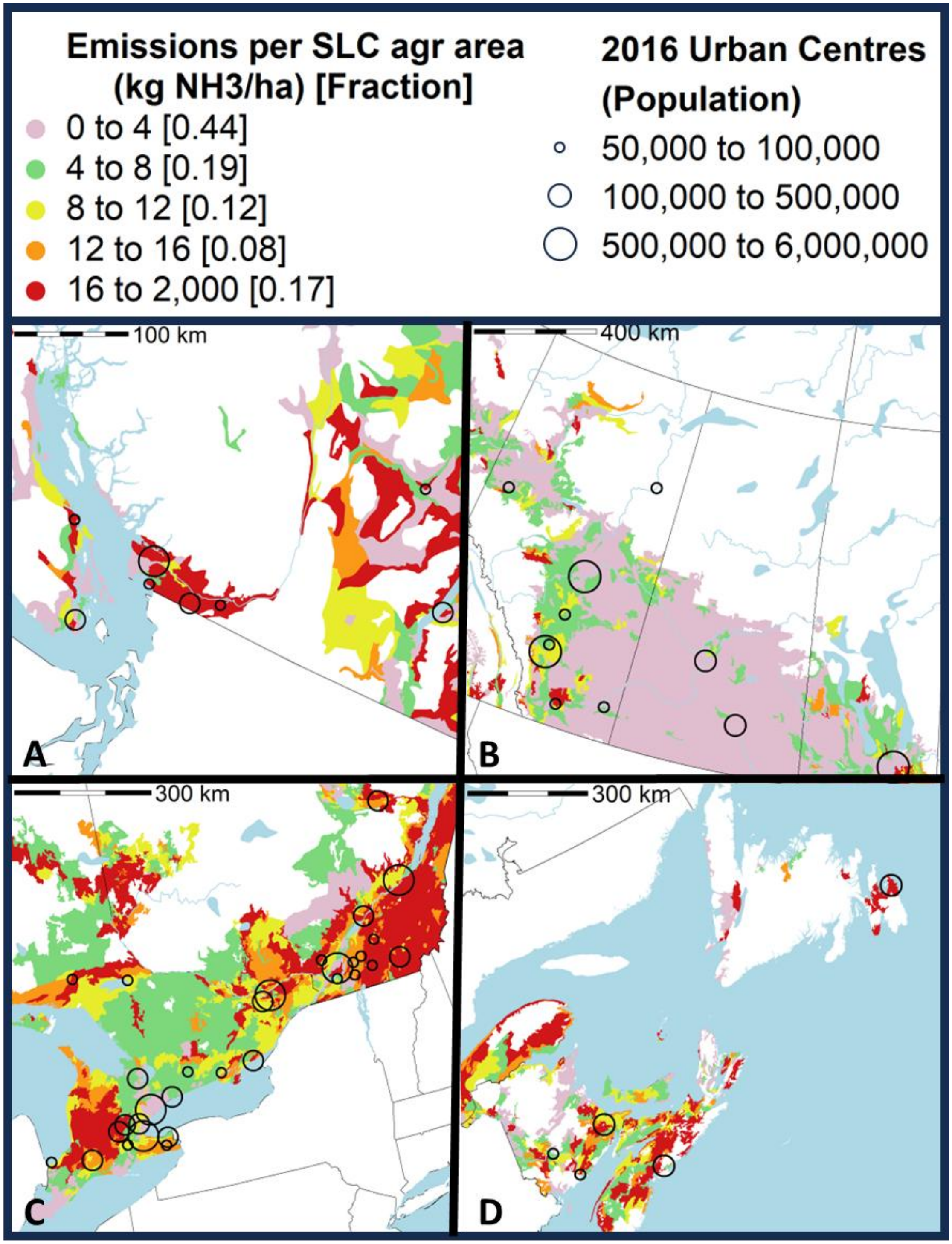
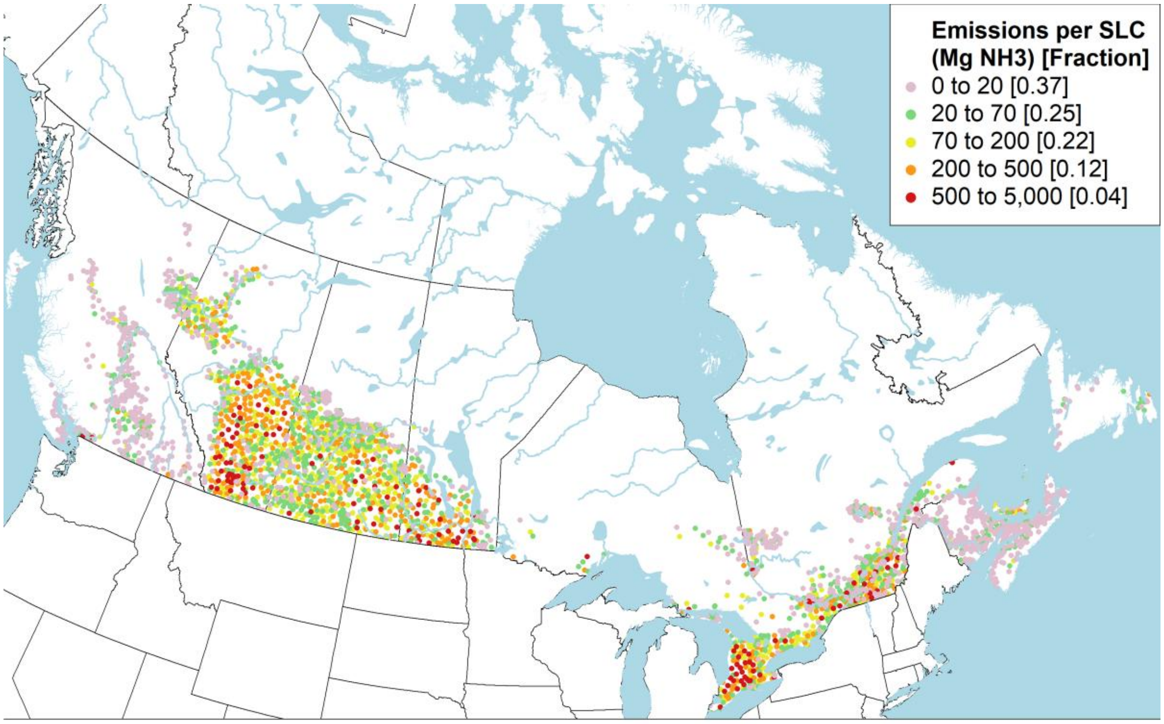


Figure 10. Ammonia emissions from livestock per hectare of agricultural land in 2021 in the (A) Fraser valley (B) Prairies (C) Great Lakes-St. Lawrence and (D) Atlantic regions. The values in square brackets in the legend indicate, at the national scale (Figure 9), the fraction of total SLCs in the associated bin and do not apply individually to insets A-D. The black circles represent urban population centres.

Figure 11 depicts the total NH_3 emissions in each SLC polygon rather than the emission intensity per unit of agricultural land. Depicting the total emissions in this way allows for comparison between polygons independent of their agricultural area, illustrating that not all regions that have high intensity of emissions have high total emissions. For example, in the Atlantic Provinces the emissions intensity is high per hectare of agricultural land (Figure 7), but there is relatively little agricultural land resulting in low total emissions. Conversely, large areas of the Prairie Provinces with low intensity of emissions have high total emissions (Figure 11). In these polygons, the majority of the area is devoted to fertilized annual crop production.

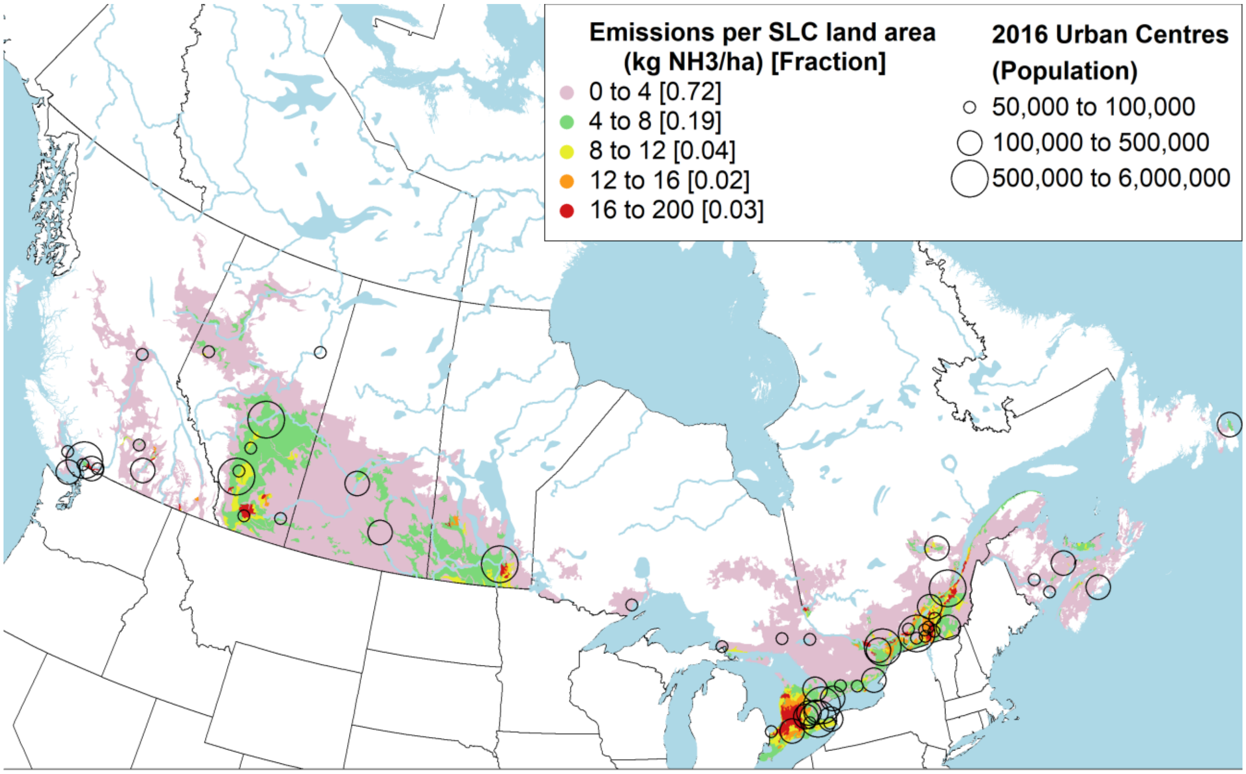
Figure 12. Ammonia emissions from livestock and fertilizer per SLC land area in 2021. The values in square brackets in the legend indicate the fraction of total SLCs in the associated bin. Open circles depict urban centres. Alternatively, the intensity of total NH_3 emissions can be expressed compared to the total land area of an SLC polygon, rather than the agricultural land. Using this approach apportions emissions over the overall landscape, decreasing the intensity for regions that have limited agricultural land area. This shows that the greatest intensity on land area basis is limited to a relatively small number of polygons in the Fraser Valley of BC, southern AB and MB, south-western ON and the southern QC. Although this only impacts a small number of regions, these polygons are frequently located near large urban centers (depicted as black circles), increasing the potential for impact on the human population.



The dots are agricultural SLCs, consisting of 3399 polygons across Canada.
The colours depict the output from TOTAL, per SLC.

Figure 11. Ammonia emissions from livestock and fertilizer per SLC in 2021.

The values in square brackets in the legend indicate the fraction of total SLCs in the associated bin.



The coloured areas are agricultural SLCs, consisting of 3399 polygons across Canada.
The colours depict the output from TOTAL, per hectare of SLC land.

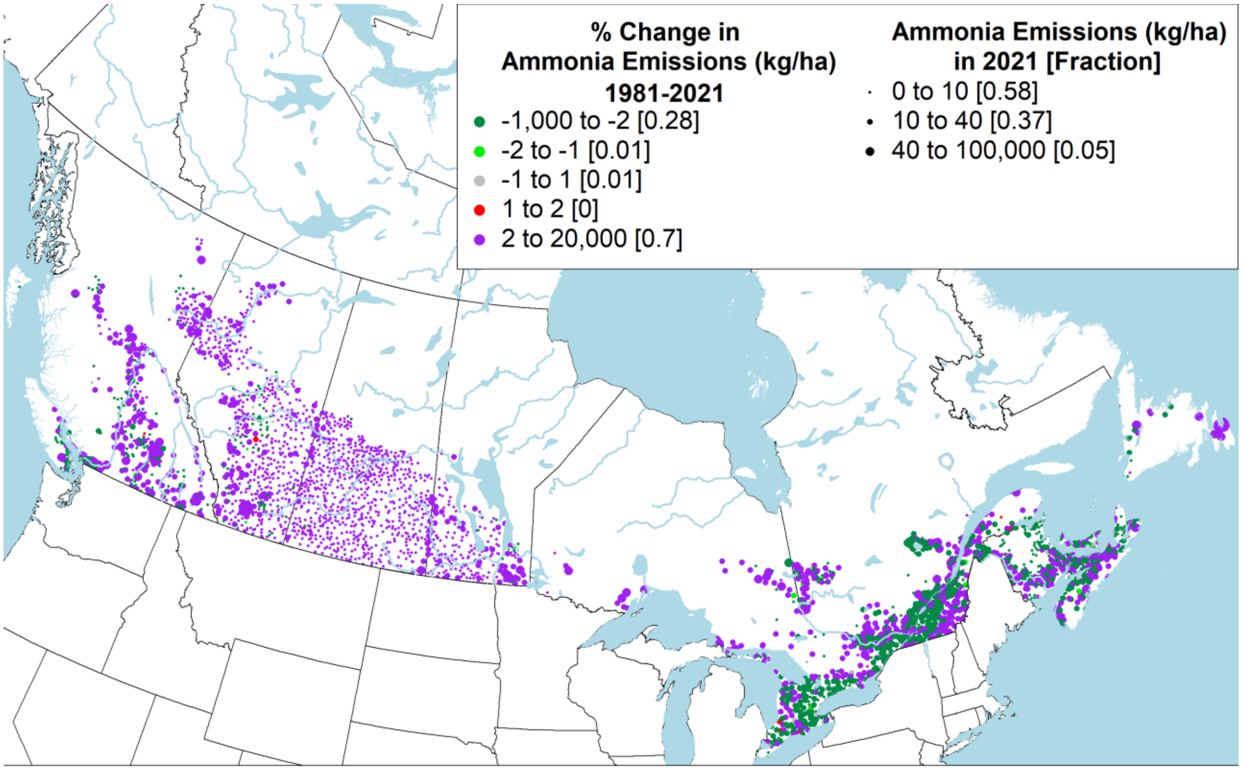
Figure 12. Ammonia emissions from livestock and fertilizer per SLC land area in 2021. The values in square brackets in the legend indicate the fraction of total SLCs in the associated bin. Open circles depict urban centres.

Figure 12. Ammonia emissions from livestock and fertilizer per SLC land area in 2021. The values in square brackets in the legend indicate the fraction of total SLCs in the associated bin. Open circles depict urban centres. While the 2021 maps show areas of high emissions from fertilizer and livestock sources, it should be noted that the percentage of farmland in each of the five emission classes changed markedly from 1981 to 2021 (Table 1). On the Prairies, less land was in the lowest emission class in 2021 than in 1981 (decline from 70% in 1981 to 43% in 2021). In Ontario and Quebec, 43% of the land was in the highest emission class in 1981, but by 2021 about 14% had moved to the next lower class. Generally, emissions are declining in the Mixed-wood Plains Region of east-central Canada due to fewer dairy and beef cattle, but rising on the Prairies due to increasing pigs, beef cattle and fertilizer. These regional changes can be viewed more clearly in Figure 13, which uses a smaller scale (~ 1 % increments) to illustrate the changes in this indicator between 1981 and 2021. Approximately one third of the SLCs declined by more than 2% while the other two thirds increased by

more than 2%. The sources of emissions among the sectors vary according to province (Table 2). This shows the change in the contribution of each sector to the total emissions from 1981 to 2021 and reflects trends in production by province.

Table 1: Percentage of total land area in agricultural regions, by province, that fall in each of the NH_3 emission intensity classes, for the selected years 1981, 2001, and 2021.

	Very Low			Low			Moderate			High			Very High		
Province	**1981**	**2001**	**2021**	**1981**	**2001**	**2021**	**1981**	**2001**	**2021**	**1981**	**2001**	**2021**	**1981**	**2001**	**2021**
AB	54.6	26.9	28.5	37.4	38.3	48.3	5.6	15.1	12.1	1.3	4.5	0.7	1.1	15.2	10.5
BC	38.2	40.7	43.4	10.2	6.1	7.7	1.1	8.1	3.1	6.2	1.5	3.5	44.2	43.6	42.3
MB	55.8	27.8	20.2	39.2	56.6	55.6	3.3	7.7	14.5	1.6	0.0	3.3	0.0	8.0	6.3
NB	84.9	84.5	85.6	11.3	11.9	11.3	1.0	2.1	3.1	0.0	1.5	0.0	2.8	0.0	0.0
NF	100.0	100.0	60.0	0.0	0.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NS	58.0	58.4	69.8	15.6	15.7	18.0	5.2	11.1	11.0	7.8	4.2	0.0	13.4	10.6	1.1
ON	5.4	9.1	11.5	13.4	23.1	24.1	21.4	18.6	18.2	18.2	16.5	16.1	41.6	32.8	30.1
PE	21.3	18.5	28.6	34.4	42.2	58.6	44.3	34.3	12.8	0.0	5.0	0.0	0.0	0.0	0.0
QC	14.3	14.6	15.5	16.4	19.5	22.1	10.8	17.3	17.5	13.3	14.7	17.3	45.2	33.9	27.7
SK	98.9	92.4	79.4	1.1	7.6	20.1	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
CA	**37.1**	**33.5**	**35.0**	**19.5**	**27.3**	**32.6**	**10.6**	**12.6**	**11.3**	**8.9**	**7.3**	**6.2**	**23.9**	**19.3**	**14.8**

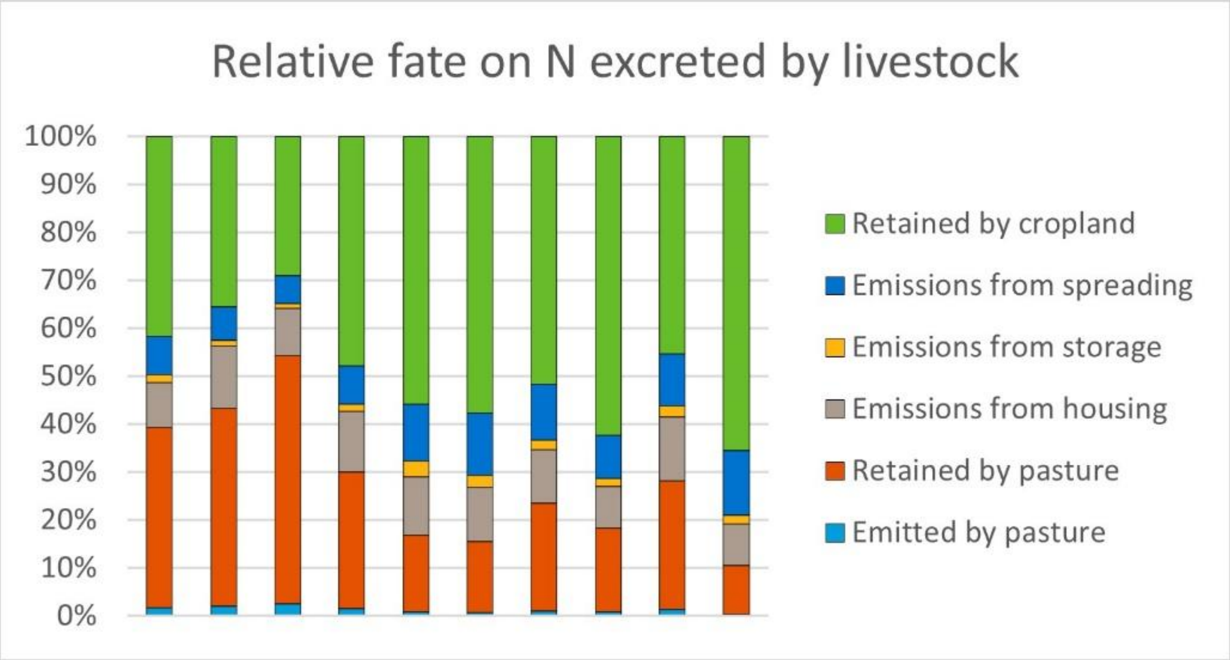


The dots are agricultural SLCs, consisting of 3399 polygons across Canada.
The colours depict the relative difference in output from T1981 and T2021, per hectare of agriculture land (CROPLND + SUMMRF + IMPAST + UNIMPST).
The dot sizes depict the output from T2021 per hectare of agriculture land (CROPLND + SUMMRF + IMPAST + UNIMPST).

Figure 13. Change in total ammonia emissions per hectare of agricultural land between 1981 and 2021. The values in square brackets in the legend indicate the fraction of total SLCs in the associated bin (negative values depict decreases).

Table 2: Percentage of ammonia emissions by sector in each province in 2021 and contribution of each province to the national totals from 1981 to 2021.

	Sector percentage contribution to NH_3 emissions in 2021 in each province					Provincial percentage contribution to national NH_3 emissions		
	Poultry	**Beef**	**Dairy**	**Swine**	**Fertilizer**	**1981**	**2011**	**2021**
BC	24.2	26.4	30.3	2.5	16.6	4.3	3.5	3.6
AB	2.2	50.6	3.6	5.6	38.0	21.0	28.7	27.4
SK	1.2	28.2	1.7	4.2	64.8	13.1	19.9	22.1
MB	3.2	21.8	3.8	25.7	45.5	8.1	11.1	11.4
ON	10.5	22.5	20.1	19.8	27.2	29.8	19.3	19.0
QC	9.1	12.1	30.2	31.4	17.2	20.1	15.3	14.4
NB	16.5	19.7	30.9	4.7	28.2	1.1	0.7	0.6
NS	24.6	23.1	34.0	1.1	17.2	1.4	0.8	0.7
PE	3.1	25.4	25.8	6.8	38.9	1.0	0.6	0.6
NF	51.5	4.9	39.6	0.0	4.1	0.1	0.1	0.2
Canada	5.8	30.0	11.7	13.8	38.7	100.0	100.0	100.0
Total (kt NH_3)						**324.6**	**369.3**	**402.8**



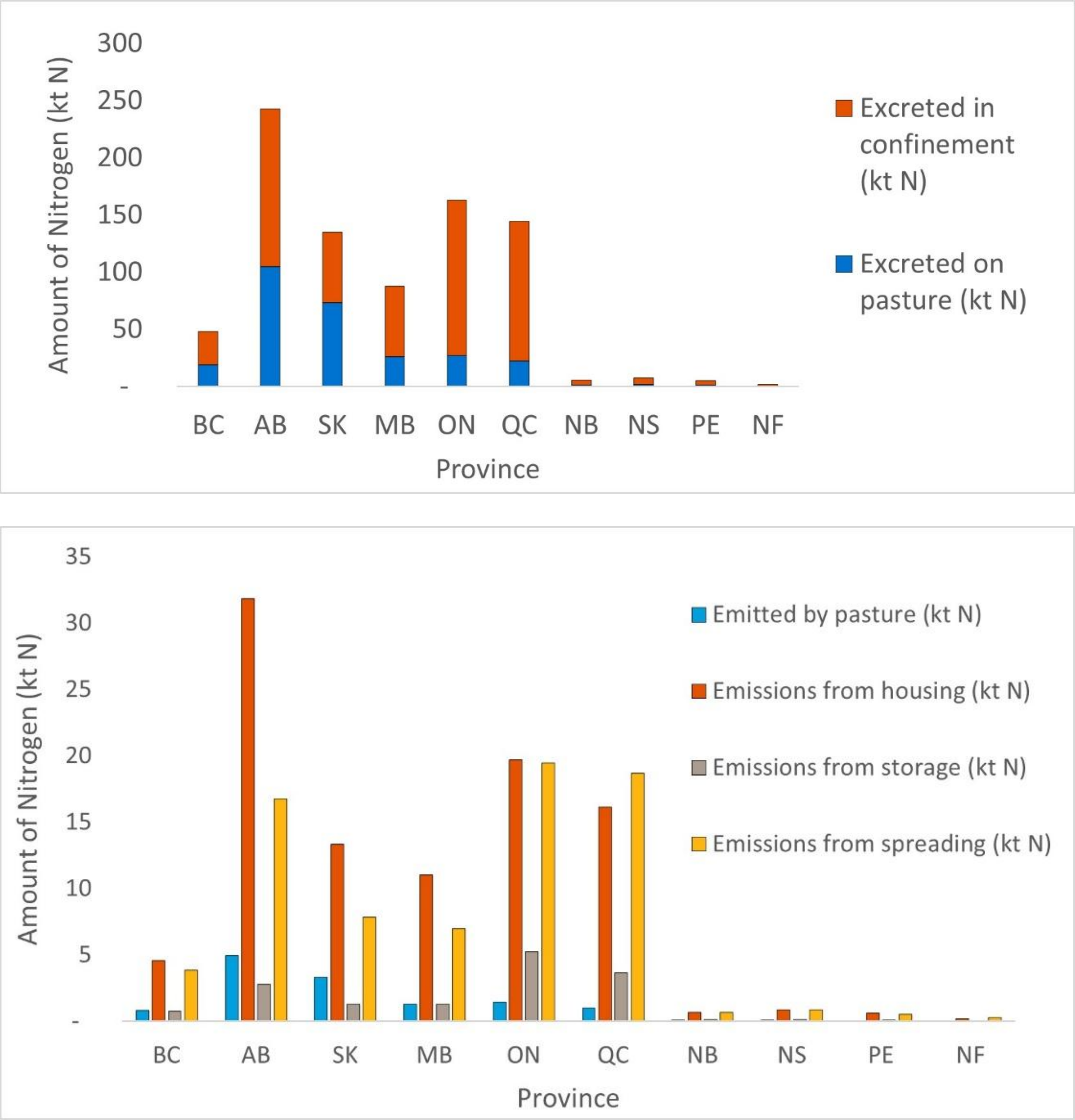


Figure 14. Upper: Percent of livestock emissions from farm sources and the percentage of N retained after application on cropland and pastures in 2021; Middle: actual values for N excretions and N retained for cropland and pastures (kt) in 2021 in each province. Lower: actual N losses (kt) by NH_3 emissions from housing, storage, spreading, and grazing in each province.

In most provinces, 29 to 58% of total N excreted is retained by arable cropland and forage soils (Upper panel, Figure 14). Feedlots in the West are the exception, given that the manure-N taken from feedlots is mostly organic and low in ammonia. The rest of the land-applied manure N is inorganic and consists largely of ammoniacal nitrogen, which is converted quickly to nitrate in warm soils, thus becoming more available to crops, but also more susceptible to losses by leaching and N_2O emissions, the latter due especially to a microbial process called denitrification which also releases N_2. In contrast, the applied organic nitrogen either slowly becomes recalcitrant (stable) with the help of soil fungi or is mineralized by microbes into ammonia, over a number of weeks to years, then is rapidly oxidized to nitrate. Note that although a lot of land-applied manure nitrogen (including that depositing as urine on pasture) consists of ammoniacal nitrogen, the dry climate on the Prairies limits the potential for leaching and denitrification but increases propensity for ammonia volatilization. The N_2O emission spikes occur after manure and fertilizer applications, following soil thaws, and rain events, while urine patches on pastures are potential hotspots for N_2O and leaching because of their very high TAN concentrations.

Of the manure produced by Canadian livestock (Middle panel, Figure 14) only the portion excreted in confinement (i.e., in barns and feedlots) can be collected and applied to replace fertilizer, while the manure deposited on pasture is less subject to ammonia emissions (urea rapidly soaks into the soil before decarboxylation to ammonia). However, pasture deposition by animals is uneven hence contributes to uneven herbage production and N uptake, although controlled (e.g. rotational) grazing can improve N distribution. Manure nitrogen excreted in confinement averages greater than 100 kt in three Canadian provinces. At an estimated $1,100 per tonne N of commercial nitrogen fertilizer in 2021, the excreted N is worth $275 million annually in AB and $165 million in QC and ON in terms of commercial N replacement value. The retained N on cropland (net of losses) is worth almost $110 million in each of these provinces. The lost (emitted) NH_3-N has an annual commercial value of $45 million in QC, $50 million in ON and $68 million in AB.

Within the manure train on farms, emissions from housing (includes feedlots) are greatest in AB due to the high emissions from dry manure collected in open feedlot pens; whereas emissions from spreading are somewhat high in QC and ON due to the large number of housed animals (Lower panel, Figure 14). In ON and QC, emissions from housing and spreading are similar but in the prairie region, high emissions from pens leaves less NH_3 in applied manure that can be lost by spreading. Most NH_3 emissions across all livestock sectors can be linked to housing (including feedlots) plus grazing (55%), along with land application of manure (37%) (Lower panel, Figure 14), while a relatively small fraction of total emissions (8%) are linked with manure storage systems, a greater proportion in other countries.

Emissions per area from pastures are low due to low N inputs onto pasture land (mostly by N fixation and atmospheric deposition) (Sheppard et al., 2018) and to rapid infiltration of urine into the soil so that the positively charged NH_4^+ released after decarboxylation of urea is adsorbed onto the negatively charged soil particles (Bittman et al., 2014). Urine patches may receive over 500 kg N ha^{-1} and are considered hotspots for N_2O emissions, so dispersion of urine patches across pastures and avoiding concentration in moist compacted areas (such as near water sources) and in 'camping' spots, so controlled or managed grazing will help mitigate the N_2O emission hotspots.

Emissions from manure storages are low across Canada because of upstream (housing) losses in feedlots, relatively cool weather during winter storage, and surface crust formation in some slurry management systems and use of vertical tanks with small surface. Covers are rarely used. The loss of NH_3 from the manure packs in cattle pens could be attributed as storage losses as this method of manure handling uses the pens as *de facto* storages.

Emissions from land spreading of manure vary considerably from region to region, ranging from a low of 6% of total excreted N in Saskatchewan to as high as 13% in Quebec and 14% in Newfoundland (Lower panel, Figure 14). Emissions from spreading are somewhat limited by a limited use of manure injection by pig farmers and due to fall application of manure on the Prairies as well as to the greater earlier losses of NH_3 from cattle pens. Injection of slurry manure is a more practical method on the Prairies than elsewhere because of relatively stone-free soils, level terrain, larger farm and tractor sizes and perhaps greater use of manure application contractors with specialized application implements. On level land on the prairies, manure is often safely injected into unfrozen soils in fall because of the cold dry winters although there is growing concern about greater spring-thaw emissions of N_2O form fall injected manure. There is no practical technology for injecting solid manure from cattle; emissions can be controlled by rapid manure incorporation into soils but this is constrained by reduced tillage. Based on the magnitude of these sources of NH_3 emissions, it is evident that mitigation efforts in Canada should examine beef 'housing' and spreading.

Emissions from livestock production and from fertilizer use across Canada are highest in May, because of manure and fertilizer applications prior to planting, and lowest during the winter, when manure is in storage and the temperatures in storage facilities and housing are relatively low, and housing ventilation is somewhat reduced. The implications of emission for human exposure can be seen in Figure 15 which depicts emissions from livestock in January and May (upper panels) in relation to the larger population centers of Canada. The seasonal and spatial pattern of emission calculated in this indicator have recently been supported by Earth observation (Figure 15, bottom panels, courtesy of Sean Ford and Mark Shephard at Environment and Climate Change Canada). Earth observations also show localized emission spikes from forest fires in western Canada in summer (not shown here) and the strong signal of ammonia emissions from the USA which can affect the air quality in Canada. Greatest exposure risk is associated with May ammonia emissions in the Lake Ontario to St Lawrence corridor, the Lower Fraser Valley of BC, and to a lesser extent Winnipeg. The effect of exposing vegetation to ammonia in spring or summer vs winter is discussed below.

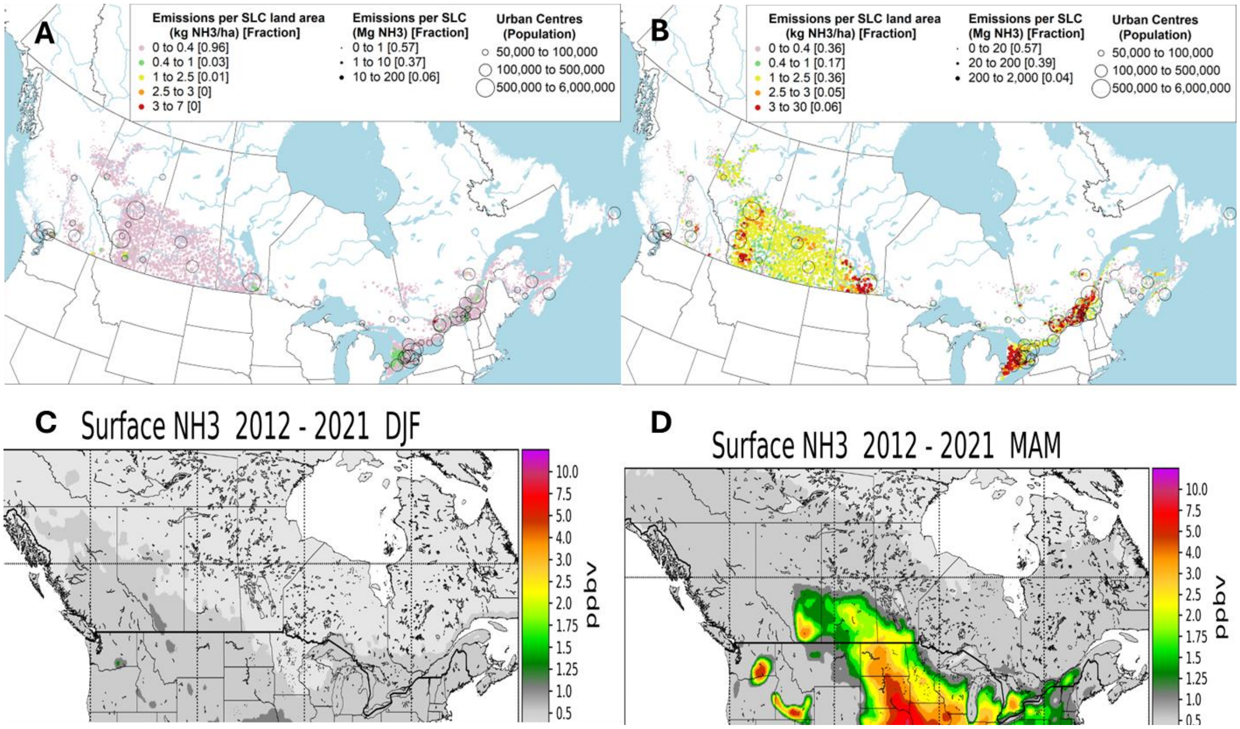


Figure 15: Top: Ammonia emissions across Canada in 2021, computed for January (A) and May (B). The values in square brackets in the legend indicate the fraction of total SLCs in the associated bin. Both maps have the same bin sizes to show contrasting seasonal emissions. Bottom: depicts the 9-year (2012 to 2021) mean map of CrIS satellite daytime NH3 surface concentration observations gridded on a 0.1° by 0.1° (~ 10 km x 10 km) spatial grid for winter (C, December, January, February) and spring (D, March, April, May), showing atmospheric ammonia in both Canada and northern USA. Satellite images were provided by Sean Ford and Mark Shephard at Environment and Climate Change Canada.

Response options

The occurrence of $PM_{2.5}$ coincides spatially with ammonia emission in Canada (https://www.epa.gov/cmaq/equates, Figure 16 upper). Importantly, it has recently been shown that to achieve reduction in $PM_{2.5}$, the cost of abating ammonia is about 10% the cost of abating NOx, emphasizing the need to prioritize ammonia reductions (Gu et al., 2021). Seasonal abatement strategies are needed in Canada where agricultural activity is compressed and temperature variation is great, compared to the USA.

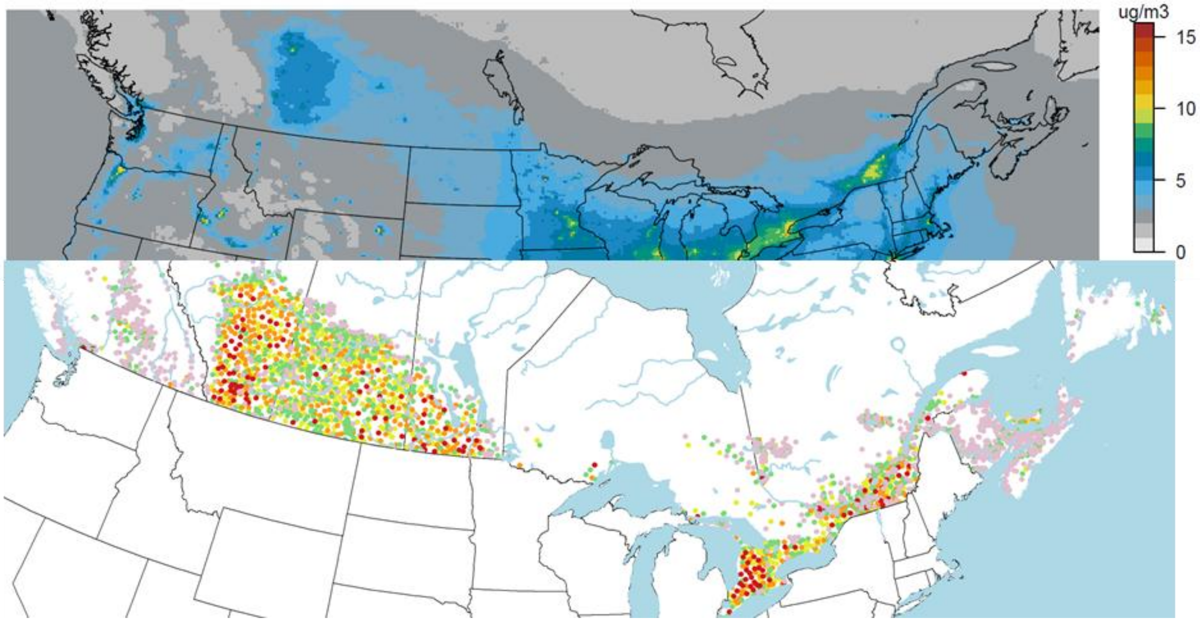


Figure 16: Top: Annual average total $PM_{2.5}$ concentrations in southern Canada and northern USA in 2016 as predicted by the U.S. EPA Community Multiscale Air Quality (CMAQ) model for the EPA's Air Quality Time Series Project (https://www.epa.gov/cmaq/equates, Courtesy of Donna Schwede, US-EPA). Bottom: Agricultural ammonia emissions for 2021 shows a similar pattern. Additional modeling research is needed to develop abatement strategies.

Beneficial management practices for reducing NH_3 losses from the many sources on livestock operations are complex. Since ammonia has a high propensity to volatilize into the atmosphere, it is important to ensure that ammonia-N applied to the soil in manure or fertilizer is stabilized (by acidification or inhibitors, respectively), rapidly infiltrated and adsorbed to soil and efficiently taken up by crops. Care must be taken to ensure that BMPs chosen to mitigate NH_3 losses do not have adverse effects on other aspects of farm operations or result in unintended environmental consequences. For example, NH_3 emissions might be mitigated through manure injection or winter bale grazing, but these practices may lead to higher emissions of N_2O than from manure broadcasting and higher leaching of nitrate than from winter housing.

The benefits and costs of the key BMPs for abating NH_3 emissions were explored using internationally accepted cost factors by Sheppard and Bittman (2013). They estimated the cost of reducing NH_3 emission to the atmosphere to be over $0.80 per kg, which is lower than the current cost for fertilizer N. When employed individually, most of these

BMPs decreased emissions from the key livestock sectors by 10% or less. The more effective BMPs focused on increased grazing of cattle (as opposed to confined feeding), avoiding oversupply of feed protein (by closely matching the amount of feed protein to animal requirements), and low emission application methods for manure and fertilizer such as surface banding, injection or rapid incorporation. When considered collectively and applied to all livestock sectors, low-cost BMPs for the reduction of NH_3 emissions have the potential to decrease overall livestock emissions in Canada, over current practices, by as much as 26%. Some of the BMPs require minimal and low-cost changes in existing practices, whereas others require specialized equipment or newly renovated facilities, such as livestock barns.

It should be emphasized that many Canadian farmers are already employing BMPs that have co-benefits of abating NH_3 emissions. Examples include the widespread use of staged, or phased, feeding of protein to pigs and chickens. In past years, there has been an increase in the use of low-emission application of liquid manure (especially injection of liquid pig manure into cropland) to reduce runoff and odour, and increased winter feeding of cattle on pastureland rather than in wintering feedlots as a cost-saving measure (Sheppard and Bittman, 2013). Furthermore, in the dairy sector, higher milk production per cow has reduced overall herd size, and in the poultry sector, increased feed efficiency and growth rates in meat (broiler) chickens have reduced the time needed for these animals to reach market weights. Canadian farmers are continually reducing emissions by improving production efficiency.

Subsurface injection at seeding (referred to as side-banding) of urea and other NH_4^+-based fertilizer has come into widespread use, especially in Western Canada. This development has offset increased emissions that would otherwise have occurred because of the industry’s shift from ammonium nitrate to urea-based fertilizers, which are much more prone to volatilization. However, large farms are challenged with reduced seeding speeds using this technology and timely seeding is vital for short growing seasons. Ultra early seeding of spring cereals my be beneficial (Collier et al., 2021).

Other management trends are leading to higher emissions, including, in the case of the dairy industry, the increased use of passively ventilated, loose (free-stall) housing and reduced grazing time. There is also a concern that an increase in composting may contribute to higher emissions, although the extent of manure composting is not well documented. While decreasing feed protein inputs is an especially effective BMP, precisely managing feed protein is more easily achieved for non-ruminants (poultry and pigs) than in cattle because of the complexities of ruminant digestion, and the extensive use of home-grown forages and pastures of varying and untested quality. Although using processing residues in feeds (e.g., dry distillers grain) reduces agricultural waste, this practice can lead to overfeeding of protein.

Canadian emissions from manure storage are typically lower than those reported by other countries because of the very cold temperatures through a major part of the storage period and the formation of crusts associated with ample bedding and dry winter weather. Losses from housing can be reduced by adding chemicals to bedding (e.g., acidifying agents like alum and sulphuric acid) and immediately segregating slurry faeces from urine in housing, using floating covers for in-barn slurry tanks as well as absorbent filters on barn vents. In Europe, there is increasing use of acidification of slurry with sulphuric acid in barns and storages or during land application to reduce emissions, and this is now being tested in Canada to also reduce methane from storages (Sokolov et al., 2019). There is a special need to develop BMPs for abating NH_3 from beef cattle in confinement, perhaps by adding lignite (Sun et al., 2016) and compost (Bai et al., 2020).

The regional and local impacts of NH_3 emissions need to be investigated in relation to temporal factors (Bittman et al., 2015). The peak emissions from agriculture, which result from manure spreading and fertilizer application, occur too early in the year to have a direct effect on smog, which is more generally a summer phenomenon. Summertime emissions do occur, however, especially from barns and storages, from manure and fertilizer applied to forages, and after harvest of winter and short season crops. Spring and summer emissions causing odours may disturb people enjoying the outdoors, but these peak emissions can perhaps be targeted by seasonal emission measures like curtailing field spreading according to weather considerations and acidifying barn floors. Early spring emissions may lead to ecological effects associated with excess N, because high ammonia levels in the atmosphere may be deleterious to new tissue in sensitive plant species and because some noxious invasive species, such as weedy grasses that respond strongly to N, undergo rapid growth in the spring. Early spring NH_3 emissions are likely to increase secondary emissions of N_2O following deposition in relatively moist and warm soils. Further study of impacts of ammonia is needed in Canada, especially setting critical levels and loadings for protection of humans and sensitive environments.

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