A gridded inventory of Canada’s anthropogenic methane emissions

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Abstract

Canada’s anthropogenic methane emissions are reported annually to the United Nations Framework Convention on Climate Change through Canada’s National Inventory Report (NIR). Evaluation of this policy-relevant inventory using observations of atmospheric methane requires prior information on the spatial distribution of emissions but that information is lacking in the NIR. Here we spatially allocate the NIR methane emissions for 2018 on a 0.1° × 0.1° grid (≈10 km × 10 km) for individual source sectors and subsectors, with further resolution by source type for the oil/gas sector, using an ensemble of national and provincial geospatial datasets and including facility-level information from Canada’s Greenhouse Gas Reporting Program. The highest emissions are from oil/gas production and livestock in western Canada, and landfills in eastern Canada. We find 11 hotspots emitting more than 1 metric ton h⁻¹ on the 0.1° × 0.1° grid. Oil sands mines in northeast Alberta contribute 3 of these hotspots even though oil sands contribute only 4% of national oil/gas emissions. Our gridded inventory shows large spatial differences with the EDGAR v5 inventory commonly used for inversions of atmospheric methane observations, which may reflect EDGAR’s reliance on global geospatial datasets. Comparison of our spatially resolved inventory to atmospheric measurements in oil/gas production fields suggests that the NIR underestimates these emissions. We also find strong spatial overlap between oil/gas, livestock, and wetland emissions in western Canada that may complicate source attribution in inversions of atmospheric data.

1. Introduction

Canada has pledged to reduce its greenhouse gas emissions to 30% below 2005 levels by 2030 under the Paris Agreement. In pursuance of this goal, it developed the Pan-Canadian Framework on Clean Growth and Climate Change (PCF) in 2016 [1]. Canada’s climate mitigation efforts include reducing emissions of methane, which accounted for 13% of national anthropogenic greenhouse gas emissions in 2018 on the basis of 100 year global warming potentials [2]. Anthropogenic methane emissions include contributions from oil/gas operations, livestock, landfills, and other smaller sources. The oil/gas sector is the most important emitter in Canada [2]. Under the PCF, Canada has committed to reduce national methane emissions from the oil/gas sector to 40%–45% below 2012 levels by 2025 and 60%–75% by 2030 [1]. Federal and provincial mitigation efforts include regulations to reduce methane leakage and venting during upstream oil/gas activities and plans to implement landfill gas recovery and waste diversion programs [3–5].

Accurate estimates of greenhouse gas emissions at the national-, facility-, and equipment-scale are necessary to define, enforce, and track the effectiveness of national and provincial climate policy. Canada’s official estimate of anthropogenic methane...
emissions is the National Inventory Report (NIR) compiled by Environment and Climate Change Canada (ECCC) [2], which is used for reporting emissions to the United Nations Framework Convention on Climate Change (UNFCCC). In addition, facilities with emissions in excess of 10 kt a$^{-1}$ CO$_2$ equivalent must report emissions to ECCC’s Greenhouse Gas Reporting Program (GHGRP) [6]. GHGRP emission reports are generally not incorporated into the NIR but are used for verification [2].

Canada’s NIR and most GHGRP estimates rely on a ‘bottom-up’ approach that combines activity data (e.g. number of cows), conditional parameters (e.g. cow age), and emission factors (e.g. methane per cow) to estimate emissions. Canada’s anthropogenic methane emissions totaled 3.7 Tg a$^{-1}$ in 2018 according to the 2020 NIR with the greatest contributions from oil/gas (45%), livestock (31%), and landfills (17%). The GHGRP including 1703 facilities reported methane emissions totaling 0.6 Tg a$^{-1}$ in 2018, most from oil/gas facilities. National methane emissions according to the NIR decreased by 3% over the 2009–2018 decade, with livestock emissions decreasing by 6% and oil/gas emissions increasing by 13% during 2009–2014 and then decreasing by 13% [2].

Bottom-up inventories of methane emissions can have large uncertainties because emission factors are highly variable. Measurements of atmospheric methane from surface sites, aircraft, ground-based remote sensing, and satellites can contribute ‘top-down’ information to improve the accuracy of inventory estimates. This typically involves the inversion of an atmospheric transport model relating emissions to atmospheric concentrations [7–9]. Emission estimates based on inversions of tower site measurements have suggested that NIR emissions are too low [10], including a 40% underestimate for oil/gas emissions in Alberta and Saskatchewan [11]. Other field measurements indicate underestimates of NIR and GHGRP emissions in oil/gas regions [12–15]. Satellite observations [10, 16–18] and joint inversions of satellite and in-situ observations [10, 19] also show this underestimate of bottom-up inventory emissions in oil/gas and livestock dominant regions of western Canada. Analyses of long-term trends in satellite methane data report no significant emission trends for the 2010–2015 [10] and 2010–2016 [16, 20] but a decreasing trend for 2010–2017 [19].

Inverse analyses of atmospheric measurements rely on the interpretation of atmospheric methane concentration gradients to infer methane emissions and therefore require prior information on where the emissions are located. Previous analyses have relied heavily on successive versions of the EDGAR bottom-up global inventory as prior information because it provides spatially-resolved emissions at 0.1$^\circ$ × 0.1$^\circ$ spatial resolution for different sectors [21]. However, EDGAR has been shown to have large errors in its spatial distribution, especially for oil/gas [22–25], in part because it relies on global datasets rather than country specific geospatial information. EDGAR is also not consistent with the national inventories reported to the UNFCCC [25]. The spatially resolved Canadian oil/gas inventory from Sheng et al [24] has been used in some inverse analyses [11, 16, 19, 26–28], but it does not match the NIR nor does it incorporate GHGRP emissions. A complicating factor in Canada is the large natural emission from wetlands [10, 29], which makes it even more important to locate anthropogenic emissions precisely.

Here we create a spatially resolved version of Canada’s NIR on a 0.1$^\circ$ × 0.1$^\circ$ grid for individual sectors/subsectors by allocating inventory emissions to source locations using country-specific geospatial datasets and incorporating GHGRP information for individual facilities. Our goal is to provide a policy-relevant gridded inventory that can be used as a prior estimate in inverse analyses of atmospheric observations to test and improve the bottom-up NIR. Our gridded inventory is for 2018 (as published in the 2020 NIR) but it can be adjusted to other years on the basis of yearly NIR and GHGRP information.

2. Data and methods

2.1. National emissions

Table 1 compiles the 2020 NIR methane emissions for Canada in 2018 by sector and subsector with the relative contributions shown in figure 1. Table 2 further disaggregates oil/gas emissions by source type. Tables 1 and 2 supplement the publicly available NIR emissions [2] with information embedded in the NIR or available for download from the UNFCCC website [30], including oil/gas emissions by source type, coal emissions by subsector, unmanaged solid waste emissions by industry, and livestock emissions by animal type. The NIR includes provincial emissions which are not included in tables 1 or 2 but are used in our spatial allocation of emissions.

The NIR includes biomass burning emissions from managed lands (23 Gg a$^{-1}$) as part of the land use and land use change sector, but we do not include them in our inventory because they would overlap with the more comprehensive gridded inventory of open fire emissions from the Global Fire Emissions Database (GFED) [31]. We do however include the small source from field burning of agricultural residues (1 Gg a$^{-1}$; table 1) because these are generally small fires that would not be properly accounted for by GFED.

2.2. Spatial allocation

We allocate the subsector/source type national emissions to a 0.1$^\circ$ × 0.1$^\circ$ grid using a number of geospatial datasets described below and listed in table S1 (available online at stacks.iop.org/ERL/17/014007/mmedia). We then scale the provincial emissions for
Table 1. Anthropogenic methane emissions in Canada (2018)*.

| Sector/Subsector                                      | NIR (Gg a$^{-1}$) | Uncertainty (%) | GHGRP (Gg a$^{-1}$) |
|------------------------------------------------------|-------------------|-----------------|---------------------|
| Oil/gas$^{b}$                                       |                   |                 |                     |
| Oil/gas fugitive—venting/flaring                   | 1650              | 11              | 222                 |
| Oil/gas fugitive—leakage                            | 852               | 22              | 93                  |
| Oil/gas combustion                                 | 683               | 22              | 92                  |
| Livestock                                           | 1120              |                 | 9                   |
| Enteric fermentation$^{c}$                          | 966               | 22              | 8                   |
| Manure management$^{d}$                             | 154               | 32              | 1                   |
| Solid waste                                         | 637               |                 | 250                 |
| Managed solid waste landfills                       | 491               | 40              | 235                 |
| Unmanaged solid waste landfills$^{e}$               | 136               | 190             | 10                  |
| Biological treatment (compost) and incineration     | 10                | 170             | 5                   |
| Residential combustion                               | 127               | 15              | 0                   |
| Coal                                                | 53                | 57              | 31                  |
| Surface mining                                      | 47                |                 | 31                  |
| Underground mining                                  | 4                 |                 | 0                   |
| Abandoned mines                                     | 2                 |                 | 0                   |
| Wastewater treatment and discharge                   | 26                | 45              | 5                   |
| Other minor sources                                 |                   |                 |                     |
| Off-road combustion                                 | 21                | 11              | 1                   |
| Road transport combustion                           | 10                | 110             | 0                   |
| Electricity generation combustion                    | 6                 | 26              | 6                   |
| Petrochemical and carbon black production           | 6                 | 16              | 4                   |
| Other minor combustion sources                      | 6                 |                 | 1                   |
| Field burning of agricultural residues              | 1                 | 64              | <1                  |
| Pig iron production                                 | <1                | 410             | <1                  |
| Total                                                | 3660              |                 | 529                 |

* Emissions are from Canada's 2020 NIR and GHGRP. Emissions greater than 1000 Gg a$^{-1}$ are rounded to three significant figures. Uncertainty estimates are as reported in the NIR; dash indicates no data. The GHGRP data represent emissions from large point sources and are thus a subset of the sources in the NIR, although the NIR does not use the GHGRP data in its emission estimates.

Oil/gas subsectors are further disaggregated by source type in table 2.

Including non-dairy cattle (771 Gg a$^{-1}$), dairy cattle (150 Gg a$^{-1}$), pigs (23 Gg a$^{-1}$), sheep (8 Gg a$^{-1}$), buffalo (6 Gg a$^{-1}$), and other livestock (8 Gg a$^{-1}$).

Including pigs (68 Gg a$^{-1}$), dairy cattle (38 Gg a$^{-1}$), non-dairy cattle (38 Gg a$^{-1}$), poultry (8 Gg a$^{-1}$), and other livestock (2 Gg a$^{-1}$).

Wood waste landfills at sawmills (56 Gg a$^{-1}$) and pulp/paper mills (80 Gg a$^{-1}$).

each sector/subsector in our gridded inventory to match the provincial estimates in the NIR. We do not directly grid the provincial emissions because the national emissions have more detailed sectoral information. We subsequently correct the spatial allocation to incorporate GHGRP emissions, keeping our national and provincial emissions equal to the NIR (section 2.3).

The 2020 NIR estimates yearly emissions for 1990–2018, so we use 2018 as the most recent year available. The provincial-level information in the NIR is updated every year and can be used for simple year-to-year adjustment of our gridded emissions, assuming a similar emissions distribution as in 2018. We do not include intra-annual variability in emissions. Monthly temperature-dependent scaling factors can be applied to distribute manure management emissions as described by Maasakkers et al [22]. Uncertainty estimates reported in the NIR for national emissions are included in table 1. The uncertainties may be larger in the gridded product because of errors in spatial allocation, and will depend on what grid averaging is applied. Scale-dependent uncertainties can be estimated from the national values using the methods presented by Maasakkers et al [22].

2.2.1. Oil/gas

Oil/gas fugitive emissions include leakage, venting, and flaring. For Alberta and Saskatchewan, we distribute upstream emissions (including oil/gas production and gas processing) using 2018 activity data reported for individual facilities. The Alberta activity data [32] include facility- and well-specific rates of gas venting, gas flaring, and oil/gas production which we use to spatially allocate upstream venting, flaring, and leakage emissions, respectively. The Saskatchewan activity data [33] include facility-specific rates of gas venting and flaring which we use to allocate upstream venting and flaring emissions. Well activity data for Saskatchewan are reported at the location of the associated facility (e.g. oil or gas battery) rather than at the individual well.

For upstream emissions in other provinces and upstream leakage emissions in Saskatchewan we allocate source type emissions (table 2) using a spatially explicit map of upstream oil/gas infrastructure.
Figure 1. Partitioning of Canada’s 2018 anthropogenic methane emissions by sector and subsector as reported in the 2020 NIR. Total national emissions for each sector/subsector are given in Table 1. For ease of visualization we combine the sector emissions, for coal, residential combustion, wastewater, and other minor sources into one larger ‘Other’ sector. Coal subsector contributions are resolved in Table 1 but not here.

Table 2. Oil/gas methane emissions in Canada (2018)*.

| Subsector/source type | Leakage (Gg a⁻¹) | Venting (Gg a⁻¹) | Flaring (Gg a⁻¹) | Combustion (Gg a⁻¹) | Total (Gg a⁻¹) |
|-----------------------|------------------|------------------|------------------|---------------------|----------------|
| Oil                   |                  |                  |                  |                     |                |
| Production b          | 192              | 533              | 17               | 37                  | 779            |
| Oil sands production  | 129              | 525              | 15c              | 33d                 | 701            |
| Transport             | <1               | <1               | <1               | <1                  | <1             |
| Refining              | 3                | 0                | <1               | <1                  | 3              |
| Abandoned wells       | 6                | NA               | NA               | NA                  | 6              |
| Gas                   |                  |                  |                  |                     |                |
| Production            | 491              | 296              | 6                | 72                  | 865            |
| Processing            | 92               | 250              | 2                | 31                  | 375            |
| Transmission          | 12               | 6                | 3                | 33                  | 54             |
| Storage               | 48               | 35               | <1               | 8                   | 91             |
| Distribution          | 6                | 2                | <1               | <1                  | 8              |
| Other e               | 40               | 3                | <1               | <1                  | 43             |
|                       | 293              | NA               | NA               | NA                  | 293            |

* This table provides further disaggregation by source type of the fugitive (leakage, venting/flaring) and combustion oil/gas subsectors from Table 1 as reported in Canada’s 2020 NIR. NA means that the source type is not applicable. Emissions summed by source type may not exactly match the subsector totals in Table 1 due to rounding.

b Not including emissions related to oil sands mining or upgrading which are reported under oil sands production.

c Includes 1 Gg a⁻¹ of emissions from well testing, servicing, and drilling.

d Includes 3 Gg a⁻¹ of emissions related to offshore and Arctic oil/gas activities.

e Primarily from accidents and equipment failures (e.g. surface casing vent flows, gas migration, etc) and including 5 Gg a⁻¹ of emissions from abandoned wells.

which we refer to as the UOG map. We create this UOG map using the spatial density of small and medium upstream oil/gas point sources as described by Zhang et al [34], weighted by the magnitude of volatile organic compound (VOC) emissions from each point source. The point-source VOC emission estimates were created for an air quality modeling version of the 2015 Air Pollutant and Emissions Inventory [35]. The UOG map does not include large sources that report air pollutant emissions in the
National Pollutant Release Inventory (NPRI), but we assume that these facilities also report methane emissions in the GHGRP. See supplementary information for further details.

For oil and gas production emissions we supplement the UOG map with data on new well locations drilled between 2016 and 2018 from Enverus [36] because the UOG map was created for 2015. We allocate 6% and 5% of oil and gas production emissions, respectively, to new wells based on the number of point sources in the Enverus data and the UOG map. We allocate emissions related to well drilling to the Enverus wells drilled in 2018.

We supplement the provincial reports and the UOG map with additional datasets for oil sands, midstream sources, and downstream sources. Refining emissions are allocated to refineries by capacity as represented in Natural Resource Canada’s CanVec cartographic database [37]. Gas transmission emissions are uniformly allocated to valve locations along transmission pipelines in the CanVec database. Gas storage emissions are allocated to storage facilities from Enverus and the Energy Infrastructure and Resource Potential of North America map [38]. Gas distribution emissions are allocated based on Statistics Canada’s population density map from the 2016 Census [39, 40]. We recognize that not all provinces have similar access to natural gas which is not considered in the population density map. Scaling by provincial gas distribution emissions after gridding accounts for some of these differences, but some rural areas may have no access to gas distribution networks.

Oil sands emissions include contributions from oil sands mines and upgrading (a process to reduce heavy oil/bitumen viscosity prior to refining [34]). Methane emissions from in-situ oil sands production are included with the oil production emissions discussed previously, following the methods of the 2020 NIR. We allocate oil sands mining emissions to a map of open-mine faces and tailings ponds [35] which is based on a 2015 map of oil sands land disturbances created by Alberta Environment and Parks. We allocate upgrading emissions uniformly to CanVec upgraders [37]. We assume that all other large oil sands facilities not included in these maps report emissions to the GHGRP.

Other oil/gas emissions are from abandoned wells, accidents, and equipment failures. We allocate abandoned well emissions from plugged and unplugged wells to the applicable wells in Enverus. We allocate accident and equipment failure emissions (e.g. surface casing vent flow emissions) to the equivalent sources in the UOG map.

Upstream oil/gas combustion emissions are allocated using facility reported gas fuel usage in Alberta and Saskatchewan [32, 33]. For the remaining provinces, we allocate upstream combustion emissions using the spatial distribution of carbon monoxide emissions in the UOG map. For combustion emissions from pipelines, refineries, and upgraders we allocate emissions to CanVec valve locations, refineries, and upgraders, respectively.

2.2.2. Livestock
We allocate enteric fermentation and manure management emissions to census subdivisions using live-stock population statistics from the 2016 Census of Agriculture [41]. Within each census subdivision we restrict emissions to agricultural areas using the Agricultural Ecumene Boundary File produced by Statistics Canada [42]. Companies may report live-stock numbers to the Census of Agriculture using the location of company headquarters for reporting, so we remove any urban grid cells from the Agricultural Ecumene map using an urban-rural map [35]. For those census subdivisions with no agricultural area on this map we restrict emissions to agricultural areas using either a map of agricultural features (e.g. barns) [37] or a map of shrublands, grasslands, and croplands [43], again removing urban areas. For animal types not in the Census of Agriculture (accounting for <0.1% of emissions) we distribute emissions uniformly over the Agricultural Ecumene.

2.2.3. Solid waste
Managed solid waste emissions are associated with landfills where municipal solid waste is disposed. We distribute emissions to the locations of CanVec landfills on a 0.1° × 0.1° grid weighted by a 0.5° × 0.5° map of waste generation from the Biomass Inventory Mapping and Analysis Tool (BIMAT) [44] which is described in more detail in the supplemental information.

Unmanaged solid waste emissions are associated with wood waste at sawmills and pulp/paper mills. We distribute emissions using the mass of waste generated for disposal in 2017 as reported by each mill in the NPRI [45]. For mills with no reported waste generation we assign the median waste generation rate.

Emissions from biological treatment of waste (composting) are allocated based on organic waste generation in BIMAT. We allocate emissions from waste incineration to wastewater, waste management, and pulp/paper mills that report dioxin/furan emissions in the 2017 NPRI as these compounds are emitted when waste is incinerated.

2.2.4. Coal
We allocate active surface mine emissions to mines in Alberta [46, 47] and British Columbia [48, 49], using 2018 coal production to distribute between mines. In the absence of mine-specific production data, we use mine count to allocate emissions to surface mines in Nova Scotia [50] and Saskatchewan [51]. We allocate underground mining emissions reported
for Nova Scotia to the Donkin mine [50]. We allocate abandoned underground mine emissions to abandoned mines by mine count in Alberta [47] and British Columbia [49], and uniformly to coal fields in Saskatchewan [51] due to a lack of data for abandoned mine locations.

2.2.5. Wastewater treatment and discharge
Wastewater treatment and discharge emissions are allocated to CanVec liquid waste facilities on a 0.1° × 0.1° grid weighted by the population density map from the 2016 Census. We use the population density map aggregated to 0.5° × 0.5° resolution assuming that wastewater plants serve regional populations.

2.2.6. Residential combustion and other minor emission sources
We allocate residential combustion emissions related to biomass fuel usage using a wood consumption map [35]. We allocate all other residential combustion emissions and commercial combustion emissions by population. For the remaining minor sources we generally use the 2016 Census or CanVec facility locations to distribute emissions as described in the supplemental information with the exception that we use a map of internal waterways [43] for domestic navigation. For agricultural residue burning emissions we use a crop residue map from BIMAT.

2.3. GHGRP emissions
There are 1703 GHGRP facilities that reported methane emissions for 2018 including 1684 facilities with usable location data and their contribution to emissions is shown in table 1. The subsectors of the GHGRP do not necessarily match our own subsectors/source types so we use the breakdown of our national emissions to disaggregate GHGRP subsector emissions as needed. For each subsector, we combine the GHGRP data (on a 0.1° × 0.1° grid) with our gridded emissions by retaining the higher emission value for each grid cell. We then apply a scaling factor to all non-GHGRP emissions so that our final emissions grid has a total emission that matches the NIR. One exception is oil refining for which the emissions in the GHGRP are greater than those in the NIR. In that case we scale down both GHGRP and non-GHGRP emissions to match the NIR.

3. Results and discussion

3.1. Spatial distribution of emissions
Figure 2 shows the total and sectoral anthropogenic methane emissions in Canada for 2018 based on the 2020 NIR as spatially distributed on our 0.1° × 0.1° grid. High emission regions are in Alberta, Saskatchewan, southern Ontario, and southern Quebec. The regional overlap between emission sectors reflects common dependencies on population density and the juxtaposition of oil/gas production and agricultural lands.

Oil/gas methane emissions total 1.7 Tg a⁻¹ and are dominated by production activities, including 32% from venting during oil production and 18% from equipment failures and accidental releases, primarily surface casing vent flows. Alberta and Saskatchewan together account for 89% of oil/gas emissions. Figure 3 shows the separate distributions of oil (0.8 Tg a⁻¹) and gas (0.9 Tg a⁻¹) emissions. Oil emissions are highest along the Alberta-Saskatchewan border while gas emissions are distributed across Alberta and southern Saskatchewan. Oil sands mining emissions are concentrated in northeastern Alberta but are relatively small (4% of national oil/gas emissions).

Livestock emissions total 1.1 Tg a⁻¹, consisting of 86% from enteric fermentation and 14% from manure management. Enteric fermentation emissions are highest in Alberta and Saskatchewan, mostly from non-dairy cattle (80% of subsector emissions), while manure management emissions are highest in Quebec and Ontario, mostly from pigs (44%) and cattle (50%).

Solid waste emissions total 0.6 Tg a⁻¹ with 77% from managed solid waste in municipal landfills, most concentrated in the densely populated regions of southern Quebec and southern Ontario.

Unmanaged solid waste emissions associated with wood waste landfills account for 21% of solid waste emissions and are highest in British Columbia (49% of national subsector emissions).

Other NIR emissions are mostly from residential combustion (127 Gg a⁻¹), coal mining (53 Gg a⁻¹), and wastewater treatment and discharge (26 Gg a⁻¹). Coal emissions are concentrated in British Columbia, accounting for 73% of national emissions. Residential combustion and wastewater emissions are concentrated in populated regions with Quebec and Ontario together accounting for 71% of national residential combustion emissions and 42% of wastewater emissions.

3.2. Methane emission hotspots
In figure 4 we identify 11 methane emission hotspots in our inventory associated with oil/gas, landfills, and livestock (table 3). We define hotspots as 0.1° × 0.1° grid cells with emissions above 1 t h⁻¹ (9 Gg a⁻¹) which represents the upper range of point sources under normal operations [8]. These hotspots account for 4% of Canada’s national emissions while hotspots by our definition account for 16% of anthropogenic emissions in the US [8] and 20% in Mexico [23].

Hotspot facilities, their locations, and the corresponding emissions are shown in table 3. Most report emissions to the GHGRP. The highest emission (32 Gg a⁻¹) is from the CNRL Horizon oil...
Anthropogenic methane emissions in Canada in 2018 as given by the 2020 NIR and spatially allocated on our 0.1° × 0.1° grid. Only grid cell emissions above 0.1 Mg a⁻¹ km⁻² are shown.

Figure 2. Anthropogenic methane emissions in Canada in 2018 as given by the 2020 NIR and spatially allocated on our 0.1° × 0.1° grid. Only grid cell emissions above 0.1 Mg a⁻¹ km⁻² are shown.

There are two additional hotspots related to oil sands mining, including the Mildred Lake and Aurora oil sands facilities operated by Syncrude Canada Ltd (15 Gg a⁻¹) and the Suncor Energy Inc. oil sands facility (12 Gg a⁻¹). The second highest emission (20 Gg a⁻¹) is from the Keele Valley municipal landfill near Toronto, which was the largest landfill in Canada before its closure in 2002. Three other hotspots are related to solid waste, including the Brady Road landfill near Winnipeg (16 Gg a⁻¹), the Powell River Division pulp mill in British Columbia (12 Gg a⁻¹), and the Ridge landfill which services southwestern Ontario (10 Gg a⁻¹). The third highest emission (17 Gg a⁻¹) is from a grid cell containing multiple oil/gas production facilities (e.g. batteries) and wells in west-central Alberta. There are two other oil/gas production hotspots related to in-situ oil sands production in the Athabasca oil sands region (10–12 Gg a⁻¹). The single livestock hotspot is an animal housing and slaughtering facility operated by JBS Foods Canada Inc. in Brooks, Alberta (10 Gg a⁻¹).
3.3. Comparison to previous bottom-up inventories

Table S2 compares our emission inventory to previously reported bottom-up inventories for Canada. Figure 5 compares our emissions distribution to the EDGAR version 5 inventory [21], which estimates anthropogenic methane emissions by sector globally on the same $0.1^\circ \times 0.1^\circ$ grid as ours and is available to 2015. The EDGAR inventory generally uses global geospatial datasets whereas we use more country-specific datasets. EDGAR estimates higher anthropogenic emissions in Canada (5.3 Tg a$^{-1}$) compared to the NIR (3.8 Tg a$^{-1}$) for 2015 with the greatest difference for fugitive oil/gas emissions (EDGAR higher...
Table 3. Methane emission hotspots in Canada (2018)\textsuperscript{a}.

| Rank | Facility(ies) | Location | Emission (Gg a\textsuperscript{-1}) |
|------|---------------|----------|------------------------------------|
| 1    | CNRL Horizon oil sands facility\textsuperscript{b} | 57.34 N, 111.76 W | 32 |
| 2    | Keele Valley landfill\textsuperscript{b} | 43.87 N, 79.50 W | 20 |
| 3    | Oil/gas production facilities | 54.55 N, 118.45 W | 17 |
| 4    | Brady Road landfill\textsuperscript{b} | 49.76 N, 97.20 W | 16 |
| 5    | Mildred Lake and Aurora oil sands facilities\textsuperscript{b} | 57.04 N, 111.62 W | 15 |
| 6    | In situ oil sands facilities | 57.25 N, 110.85 W | 12 |
| 7    | Powell River Division pulp mill | 49.87 N, 124.55 W | 12 |
| 8    | Suncor Energy oil sands facility\textsuperscript{b} | 57.00 N, 111.47 W | 12 |
| 9    | Ridge landfill\textsuperscript{b} | 42.31 N, 82.06 W | 10 |
| 10   | In situ oil sands facilities | 55.55 N, 110.85 W | 10 |
| 11   | JBS Foods Canada Inc. stockyard\textsuperscript{b} | 50.60 N, 111.88 W | 9 |

\textsuperscript{a}Hotspots are defined as emission greater than 1 t h\textsuperscript{-1} (9 Gg a\textsuperscript{-1}) per 0.1° × 0.1° grid cell in our inventory. See map in figure 4. All hotspots except 3, 6, 10 are dominated by a single facility, in which case the emission listed is for that facility. Hotspots 3, 6, 10 include multiple upstream facilities within the grid cell, in which case the emission given is the total for the grid cell and the location given is the center of the grid cell.

\textsuperscript{b}Emission shown reflects reporting to the GHGRP.

Figure 5. Comparison of Canada’s anthropogenic methane emissions in our spatially explicit version of Canada’s 2020 NIR to the EDGAR v5 inventory, both on the same 0.1° × 0.1° grid. Here we show the emissions difference (right panel with national difference inset) between our work for 2018 and EDGAR v5 for 2015 (left panel with national total inset). Sector differences are show in figure S1.

EDGAR v5 (2015)  This work - EDGAR v5

Total 5.3 Tg a\textsuperscript{-1}  Difference -1.6 Tg a\textsuperscript{-1}

Methane (Mg a\textsuperscript{-1} km\textsuperscript{-2})

Difference between our work and EDGAR v5 (Mg a\textsuperscript{-1} km\textsuperscript{-2})

by 76%). EDGAR oil and gas emissions are concentrated at a small number of production sites and along pipelines, respectively, leading to higher estimates in our inventory for most production regions (see figure S1). EDGAR solid waste emissions are also more concentrated in a small number of grid cells compared to our work (figure S1). EDGAR has 76 methane emission hotspots by our definition associated with oil production and landfills that account for 49% of national emissions, which is much greater than our 11 such hotspots accounting for only 4% of our emissions.

Figure 6 shows methane emissions by sector for the Greater Toronto Area (GTA; including the City of Toronto and four surrounding municipalities) in our inventory for 2018 and in the Facility Level and Area Methane Emissions (FLAME-GTA) inventory \cite{52} for 2016. The FLAME-GTA inventory uses more local information than our national-scale inventory. There is generally good agreement in the sectoral breakdown of emissions. Our emissions (92 Gg a\textsuperscript{-1}) are slightly higher than FLAME-GTA (81 Gg a\textsuperscript{-1}), primarily due to solid waste. Ars et al \cite{53} find from a vehicle-based survey that the largest emissions in the GTA are from the waste sector, consistent with our work, though they find much lower emissions from the Keele Valley landfill (0.2–4 Gg a\textsuperscript{-1}) than in our inventory and FLAME-GTA (20 Gg a\textsuperscript{-1}), which are based on the GHGRP.

We also compare the oil/gas emissions in our inventory to a bottom-up lifecycle analysis from the Oil‐Climate Index (OCI) model \cite{54,55} as a means of evaluating the oil/gas emissions in the NIR. The OCI model uses detailed information on oil/gas infrastructure to estimate greenhouse gas emissions associated with upstream activities (see supplemental
information for details). The OCI model estimates higher fugitive oil/gas emissions (1.9 Tg a⁻¹) for 2015 than the 2020 NIR (1.7 Tg a⁻¹ for 2015). The higher emissions in the OCI model are in part explained by higher emissions from flaring which account for 20% of emissions in the OCI model and only 1% in the NIR.

ECCC generated an unpublished gridded methane inventory for Canada based on a 2013 national VOC inventory [56]. Our figure 2 can be compared to the corresponding emission maps provided by Chan et al [11] but interpretation is difficult because of the lack of inventory information.

3.4. Comparisons to emissions inferred from atmospheric measurements

Atherton et al [12] used vehicle-based surveys of methane plumes in 2015 to infer oil/gas methane emissions of 112 Gg a⁻¹ for a part of the Montney gas development region in northeastern British Columbia. Their estimate is higher than British Columbia’s total provincial emissions in the NIR (78 Gg a⁻¹ in 2015), leading to the lower estimate in our inventory (67 Gg a⁻¹) for the Montney region.

Johnson et al [13] used airborne measurements in 2016 to study two oil/gas production regions in central Alberta. They estimated 3.1 t h⁻¹ for the gas-dominated Red Deer region and 24.5 t h⁻¹ for the heavy oil-dominated Lloydminster region. A separate ground-based field study by Zavala-Araiza et al [57] in 2016 estimated an emission rate of 4.8 t h⁻¹ for the same Red Deer region. Our oil/gas emission rate is similar (3.5 t h⁻¹) for the Red Deer region and much lower (4 t h⁻¹) for Lloydminster. Johnson et al compared their measurements to a regional bottom-up inventory based on ECCC methods and also found an underestimate for the Lloydminster region, which they attributed to unaccounted for venting emissions from cold oil production.

MacKay et al [15] compiled site-level emissions from nine vehicle-based measurement campaigns across Canada and similarly attributed high emissions to venting during cold oil production. They found the highest site emissions from Lloydminster with a cumulative methane emission rate of 2.2–3.4 t h⁻¹ for all sites measured while they found a lower cumulative rate of 0.5 t h⁻¹ in Red Deer. Their estimates generally agree with our work but they do not necessarily include all facilities present in each region and therefore only provide a lower bound on emissions.

Baray et al [14] used aircraft measurements in 2013 to infer emissions of 19.6 t h⁻¹ for the Athabasca oil sands region. Our oil/gas emissions in this region are lower at 8.3 t h⁻¹ (5.4 t h⁻¹ from GHGRP reporting). Baray et al find that their top-down emission estimates for individual facilities are consistently higher than the GHGRP with the exception of the CNRL Horizon oil sands facility, which reported 4.8 t h⁻¹ for 2013 compared to the top-down estimate of 3.6 t h⁻¹.

3.5. Spatial overlap with wetland emissions

A challenge in quantifying anthropogenic methane emissions in inversions of atmospheric observations over Canada is the large and uncertain contribution from wetlands [10, 58]. Desjardins et al [59] previously noted the difficulty in separately inferring livestock and wetland emissions based on top-down aircraft observations of methane fluxes in Ontario. In figure 7 we show wetland emissions for 2018 from the mean of the WetCHARTS inventory ensemble version 1.2.1 [29], compared to the anthropogenic emissions in our work. The wetland emissions (12 Tg a⁻¹) are much larger than the anthropogenic emissions (3.7 Tg a⁻¹). On the 0.5° × 0.5° resolution WetCHARTS grid, we find that 1.0 Tg a⁻¹ (27%) of our anthropogenic emissions are in grid cells with a 30% or greater total emissions contribution from wetlands. Inversions of satellite observations and tower measurements have indicated an underestimate of anthropogenic emissions in western Canada [10, 11, 17, 18, 20], and we find a high degree of spatial overlap with wetlands in these regions, including central Alberta and southern Saskatchewan. The large discrepancies in the spatial distribution of wetland emissions between different bottom-up inventories [60] further complicates the problem.

![Figure 6. Methane emissions for the Greater Toronto Area in the FLAME-GTA inventory (2016) [52] and in our work (2018) sampled over the same domain (43.3–44.5 N, 78.5–80.1 W)]. Sectors match those defined in table 1 with the exception that we use gas emissions as defined in table 2.](image-url)
Wetland emissions in Canada have a large seasonality [61] that could enable separation from anthropogenic emissions in top-down emission estimates. Satellite observations of methane by solar backscatter are mainly limited to summer months and may not be able to exploit this seasonal separation. Baray et al [10] showed that a joint inversion of tower and satellite observations was able to adequately separate Canada’s anthropogenic and wetland emissions on a national scale but not by province.

3.6. Missing sources

Our inventory is limited by design by the emission sectors included in the 2020 NIR but we recognize that there are potential missing sources. Ars et al [53] found that engineered waterways in Toronto, like the Keating Channel, may be a source of methane emissions missing in bottom-up inventories. Delwiche et al [62] found that hydropower reservoirs may have large regional methane emission contributions in Canada. Flooded land sources were addressed in the 2019 IPCC refinement [63]. There are existing gridded inventories of methane emissions from hydropower [62] that should be included in inverse modeling studies in addition to our inventory.

4. Conclusions

We have created a gridded inventory (0.1° × 0.1° resolution) of Canada’s 2018 anthropogenic methane emissions as a spatially explicit version of the 2020 NIR submitted to the UNFCCC. Our gridded inventory can be used as prior estimate in inversions of atmospheric methane observations with the goal of providing evaluation of the NIR as the policy-relevant estimate of Canada’s methane emissions. Our inventory uses country-specific geospatial datasets including the locations of oil/gas facilities, landfills, and coal mines, incorporating facility-specific emissions as reported in Canada’s GHGRP. Our emission grids are available by subsector and oil/gas source type for 2018 and can be adjusted to other years using the year-specific annual data from the NIR.

Oil/gas activities (45%), livestock (31%), and solid waste (17%) are the dominant sources contributing to Canada’s 2018 methane emission estimate of 3.7 Tg a⁻¹ as reported in the 2020 NIR. Our gridded inventory shows substantial overlap of oil/gas and livestock emissions in western Canada. We identified 11 hotspots with emissions greater than 1 t h⁻¹ (9 Gg a⁻¹) on the 0.1° × 0.1° grid including four solid waste landfills, six oil/gas production hotspots, and one livestock processing facility. These emission hotspots account for 4% of national emissions.

Total national emissions in our inventory, as reported in the 2020 NIR, are lower than the EDGAR v5 gridded global inventory, particularly for the oil/gas sector. EDGAR generally has more localized regions of high emission on the 0.1° × 0.1° grid. It uses global geospatial datasets for allocation of emissions and we therefore expect it to be less accurate than our inventory. We estimate similar sectoral
emissions for Toronto as the FLAME-GTA inventory which uses more local information. Further comparison of our inventory with emission estimates inferred from atmospheric measurement campaigns in oil/gas production fields suggests that the NIR is too low for that sector. National-scale inversions of atmospheric data using our gridded inventory as prior estimate would provide a more comprehensive evaluation of Canada’s anthropogenic emissions as reported in the 2020 NIR. Separating anthropogenic methane emissions from the larger and highly uncertain natural wetlands source is however a major challenge for these inversions, particularly in western Canada where there is significant spatial overlap.

Data availability

Our gridded inventory for Canada’s 2018 methane emissions includes an emission grid for each sector/subsector/source type of tables 1 and 2. The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.7910/DVN/CC3KLO [64].

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