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 (UNFCCC) through Canada's National Inventory Report (NIR). Evaluation of these emissions using observations of atmospheric methane requires prior information on emission locations but that information is lacking in the NIR. Here we spatially allocate the NIR methane emissions for 2018 on a 0.1º x 0.1º grid (≈ 10 km x 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 0.1º x 0.1º 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, especially for oil/gas. 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 national-scale inversions.

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, the second most important anthropogenic greenhouse gas, which accounted for 13% of national greenhouse gas emissions from human activities in 2018 [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. Federal mitigation efforts include regulations to reduce methane leakage and venting during upstream oil/gas activities [3] and long-term plans to implement landfill gas recovery and waste diversion programs [4]. Parallel regulatory efforts exist at the provincial level for upstream oil/gas activities and landfills [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, 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 [12-14]. Satellite observations indicate an underestimate of emissions in western Canada [10,15] which have been attributed to livestock and oil/gas [16,17], and further indicate no significant emission trend over the 2010-2016 period [15,18]. Joint inversions of satellite and in-situ measurements that take advantage of the seasonality of wetlands to separate natural and anthropogenic emissions support an underestimate of anthropogenic emissions in western Canada [10,19]. Baray et al. [10] performed a joint inversion for 2010-2015 and did not find a significant emission trend while Lu et al. [19] found a decreasing trend for 2010-2017.

Inverse analyses of atmospheric measurements rely on the interpretation of atmospheric methane 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° x 0.1° spatial resolution for different sectors [20]. However, EDGAR has been shown to have large errors in its spatial distribution, especially for oil/gas [21-24], and it is generally not consistent with the national inventories reported to the UNFCCC [24]. The spatially resolved Canadian oil/gas inventory from Sheng et al. [23] has been used in some inverse analyses [11,15,19,25-27], 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 [10,28], 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° x 0.1° grid for individual sectors/subsectors by allocating inventory emissions to source locations and incorporating GHGRP information for individual facilities. The gridded inventory 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 [29], 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.

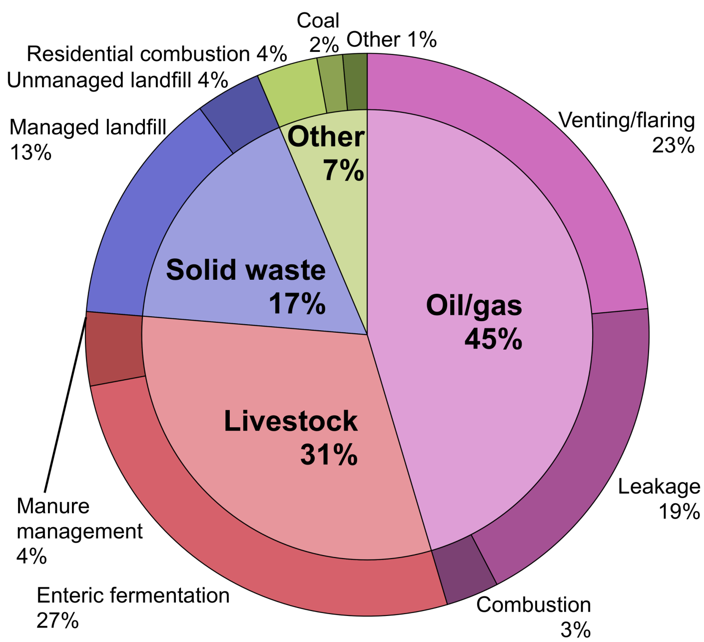

Figure 1. Partitioning of Canada's 2018 anthropogenic methane emissions by sector and subsector as reported in the 2020 National Inventory Report (NIR). Total national emissions for each sector/subsector are given in Table 1. Coal subsector contributions are resolved in Table 1 but not here.

The NIR includes biomass burning emissions from managed lands (23 Gg a^{-1}), reported in the land use and land use change sector that we do not include because they would overlap with more comprehensive gridded inventories of open fire emissions such as the Global Fire Emissions Database [30]. 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 may not be properly accounted for in the open fire inventories.

2.2. Spatial allocation

We allocate the subsector/source type national emissions to a 0.1º x 0.1º grid using a number of geospatial datasets described below. We then scale the provincial emissions for 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

Sector/Subsector	NIR Gg a^{-1}	Uncertainty %	GHGRP Gg a^{-1}
Oil/gas[b]	1650		222
Oil/gas fugitive - venting/flaring	852	11	93
Oil/gas fugitive - leakage	683	22	92
Oil/gas combustion	110	140	37
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

sectoral information. We subsequently correct the spatial allocation to incorporate GHGRP emissions (section 2.3).

Table 1. Anthropogenic methane emissions in Canada (2018)[a]

[a] Emissions are from Canada's 2020 National Inventory Report (NIR) and Greenhouse Gas Reporting Program (GHGRP). Emissions greater than 1000 Gg a^{-1} are rounded to 3 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 estimates of emissions.

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

[c] 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}).

[d] 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}).

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

Subsector/source type	Leakage Gg a^{-1}	Venting Gg a^{-1}	Flaring Gg a^{-1}	Combustion Gg a^{-1}	Total Gg a^{-1}
Oil	192	533	17	37	779
Production[b]	129	525	15[c]	33[d]	701
Oil sands production	54	8	2	4	68
Transport	< 1	< 1	< 1	< 1	< 1
Refining	3	0	< 1	< 1	3
Abandoned wells	6	NA	NA	NA	6
Gas	491	296	6	72	865
Production	92	250	2	31	375
Processing	12	6	3	33	54
Transmission	48	35	< 1	8	91
Storage	6	2	< 1	< 1	8
Distribution	40	3	< 1	< 1	43
Other[e]	293	NA	NA	NA	293

Table 2. Oil/gas methane emissions in Canada (2018)[a]

[a] 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 National Inventory Report (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.

The 2020 NIR estimates emissions for 1990-2018, so we use 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 that the relative distribution within each province is the same 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 over the year as described by Maasakkers et al. [21]. 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. [21].

2.2.1. Oil/gas

Oil/gas fugitive emissions include leakage, venting, and flaring. For Alberta and Saskatchewan, we distribute upstream emissions using 2018 activity data reported for individual facilities. The Alberta activity data [31] 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 [32] 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 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. [33], 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 (APEI) which we will refer to as the model-APEI [34]. 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.

For oil and gas production emissions we supplement the UOG map with data on new well locations drilled between 2016 and 2018 from Enverus [35] 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 [36]. Gas distribution emissions are allocated based on Statistics Canada’s population density map from the 2016 Census [37,38]. We recognize that not all provinces have similar access to natural gas which is not considered in the population density map but scaling by provincial gas distribution emissions after gridding accounts for at least some of these differences.

Oil sands emissions include emissions from oil sands mines and upgrading (a process to reduce heavy oil/bitumen viscosity prior to refining [33]). 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 as used in the 2015 model-APEI and 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 related to 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 [31,32]. 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 livestock population statistics from the 2016 Census of Agriculture [40]. Within each census subdivision we restrict emissions to agricultural areas using the Agricultural Ecumene Boundary File produced by Statistics Canada [41]. Companies may report livestock 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 as designated by an urban-rural map provided by the 2015 model-APEI. 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 [42], 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 CanVec landfills on a 0.1º x 0.1º grid weighted by a 0.5º x 0.5º map of waste generation from the Biomass Inventory Mapping and Analysis Tool (BIMAT) [43] which incorporates 2016 Census data as well as municipal waste collection data for Ontario. We aggregate the BIMAT map (10 x 10 km^2) because we assume waste generation will not always occur within 10 km of a landfill. For those landfill sites that have no waste generation in the BIMAT map we assign the median waste generation per landfill.

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 [44]. 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 [45,46] and British Columbia [47,48], 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 [49] and Saskatchewan [50]. We allocate underground mining emissions reported for Nova Scotia to the Donkin mine [49]. We allocate abandoned underground mine emissions to abandoned mines by mine count in Alberta [46] and British Columbia [48], and uniformly to coal fields in Saskatchewan [50] 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 0.1º x 0.1º grid weighted by the population density map from the 2016 Census. We use the population density map aggregated to 0.5º x 0.5º 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 from the 2015 model-APEI. We allocate all other residential combustion emissions and commercial combustion emissions by population. The 2016 Census also provides maps of the subset of the population engaged in certain economic activities (e.g., mining) that we use to allocate combustion emissions from manufacturing, mining, construction, and agriculture.

Public electricity and heat production emissions are allocated to the corresponding fuel-specific CanVec power plants by plant capacity. Pulp and paper combustion emissions are allocated to biomass power plants. Road, aviation, and railway transport emissions are allocated to the corresponding CanVec infrastructure with road emissions weighted by population at 0.5º x 0.5º resolution. Domestic navigation emissions are allocated to internal waterways [42], and all other transport emissions are allocated by population.

Emissions from the petrochemical and carbon black production industry are allocated to CanVec refineries while all other industries are completely covered by the GHGRP (see section 2.3). Agricultural residue burning emissions are allocated by crop type based on the BIMAT maps of median crop residue generation for 1985-2016.

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 desired 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 0.1º x 0.1º 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 the emissions total matches the NIR. One exception is oil refining for which the emissions in the GHGRP are greater than those in the NIR so we scale down all 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 0.1º x 0.1º grid. There are high emission regions 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

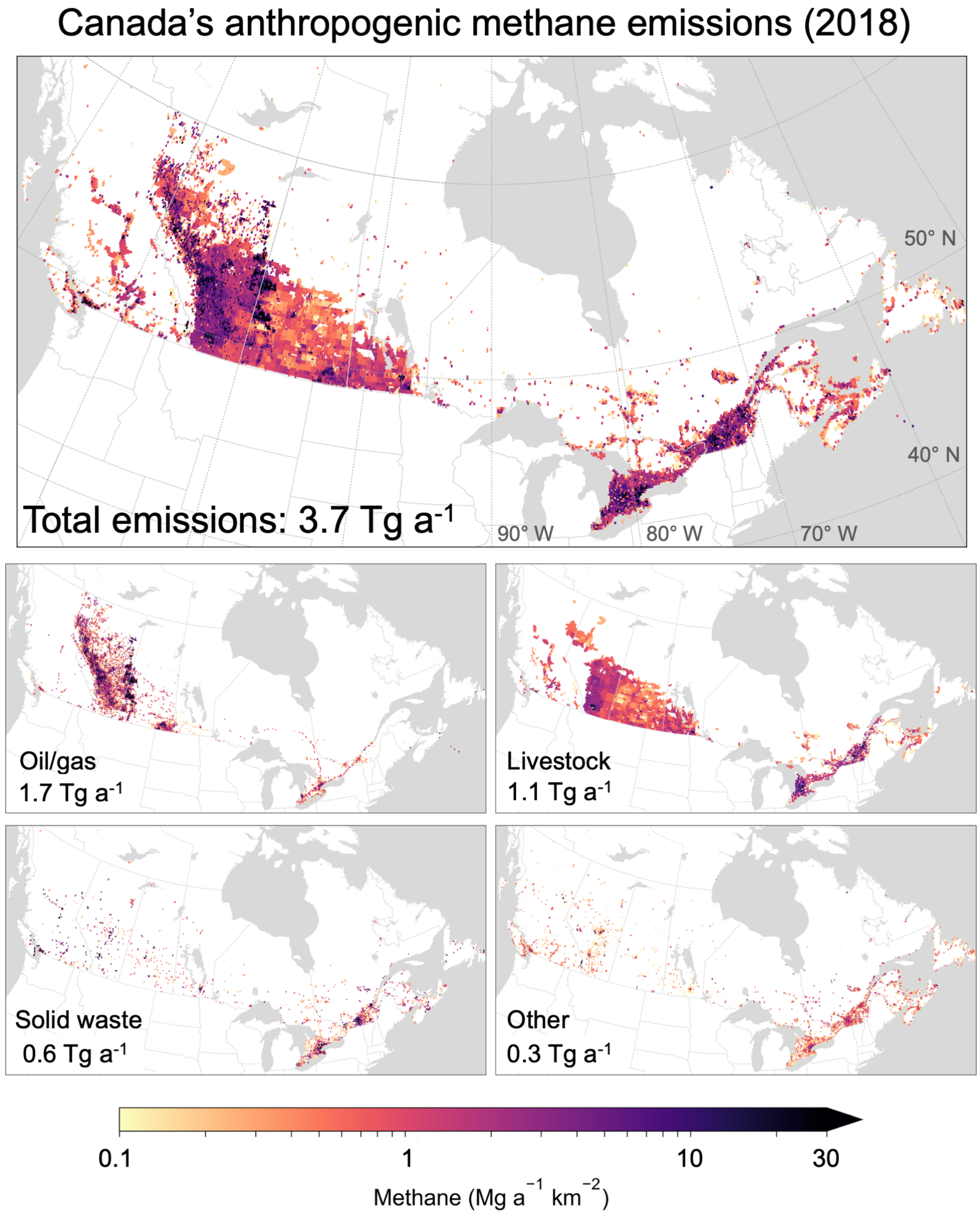

Figure 2. Canada's anthropogenic methane emissions in 2018 as given by the 2020 National Inventory Report (NIR) and spatially allocated on our 0.1º x 0.1º grid. Only grid cell emissions above 0.1 Mg a^{-1} km^{-2} are shown.

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 and in southeastern Saskatchewan 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. Based on NIR provincial emissions, enteric fermentation emissions are

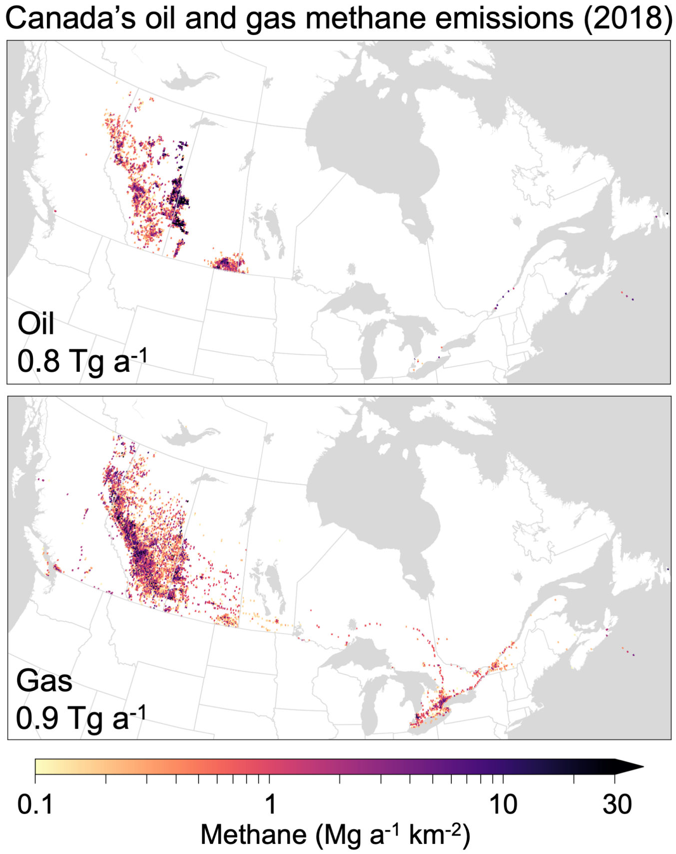

Figure 3. Canada's oil and gas methane emissions in 2018 as given by the NIR and allocated on our 0.1° x 0.1° grid. Only grid cell emissions above 0.1 Mg a^{-1} km^{-2} are shown.

highest in Alberta and Saskatchewan with non-dairy cattle accounting for 80% of subsector emissions. Manure management emissions are highest in Quebec and Ontario with pigs and cattle (dairy/non-dairy) accounting for 44% and 50% of subsector emissions, respectively.

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° x 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

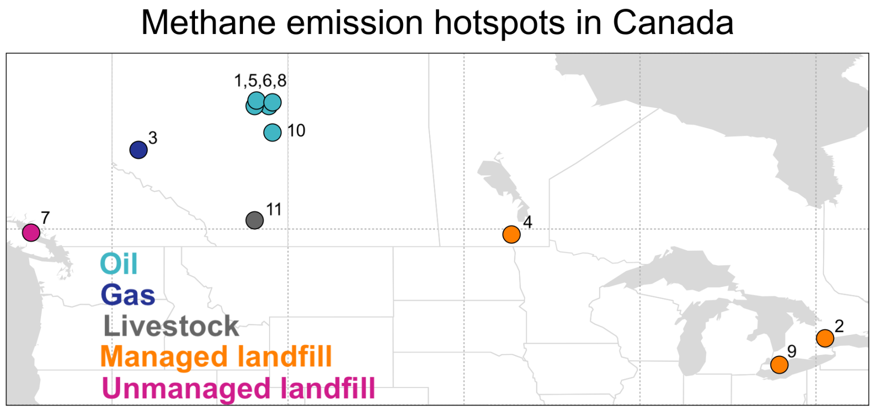

Figure 4. Methane emission hotspots in our inventory as defined by 0.1° x 0.1° grid cell emissions above 1 t h^{-1} (9 Gg a^{-1}). The rank for each hotspot is given and further details are in table 3.

Table 3. Methane emission hotspots in Canada (2018)[a]

Rank	Facility(ies)	Location	Emission Gg a^{-1}
1	CNRL Horizon oil sands facility[b]	57.34 N, 111.76 W	32
2	Keele Valley landfill[b]	43.87 N, 79.50 W	20
3	Oil/gas production facilities	54.55 N, 118.45 W	17
4	Brady Road landfill[b]	49.76 N, 97.20 W	16
5	Mildred Lake and Aurora oil sands facilities[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[b]	57.00 N, 111.47 W	12
9	Ridge landfill[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[b]	50.60 N, 111.88 W	9

[a] Hotspots are defined as emission greater than 1 t h^{-1} (9 Gg a^{-1}) per 0.1° x 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.
[b] Emission shown reflects reporting to the GHGRP.

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 [22].

Hotspot facilities, their locations, and the corresponding emissions are shown in table 3. Most facilities report emissions to the GHGRP. The highest emission (32 Gg a^{-1}) is from the CNRL Horizon oil sands facility (including surface mine and processing plant) in the Athabasca oil sands region. 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

Figure 5 compares our spatially explicit representation of the NIR to the latest version (v5) of the EDGAR inventory [20], which estimates anthropogenic methane emissions by sector globally on the same 0.1^o x 0.1^o grid as ours and is available to 2015. EDGAR estimates Canada's anthropogenic emissions as 5.3 Tg a^{-1} for 2015 while the NIR estimates 3.8 Tg a^{-1} for 2015 (29% lower). The greatest difference on the national scale is for fugitive oil/gas emissions, with the NIR estimating 1.7 Tg a^{-1} for 2015 compared to 3.0 Tg a^{-1} in EDGAR. Spatially, 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. The distribution of livestock emissions in EDGAR is similar to our work while EDGAR solid waste emissions are more concentrated in a small number of grid cells. EDGAR has 76 methane emission hotspots with grid cell emissions above 1 t h^{-1} that account for 49% of national emissions, which is much greater than our 11 such hotspots accounting for only 4% of our emissions. Most EDGAR hotspots are related to oil production and landfills.

Figure 6 shows methane emissions by sector for the Greater Toronto Area (GTA) in our inventory for 2018 and in the Facility Level and Area Methane Emissions (FLAME-GTA) inventory [51] for 2016. The GTA includes the central City of Toronto and the four surrounding municipalities. Our emissions (92 Gg a^{-1}) are slightly higher than the FLAME-GTA inventory (81 Gg a^{-1}), primarily due to higher estimates of solid waste emissions (68 versus 60 Gg a^{-1}). Mostafavi Pak et al. [51] find that EDGAR v5 estimates higher emissions in 2015 (96 Gg a^{-1}) than the FLAME-GTA inventory but has lower solid waste emissions offset by higher wastewater emissions. Ars et al. [52] compare the FLAME-GTA inventory to vehicle- and bicycle-based surveys of methane emissions and find that the waste sector is the largest source in the GTA though they find lower emissions from the largest solid waste facilities, including the Keele Valley landfill with emissions estimated at 0.2-4 Gg a^{-1} based on inverse modeling (13 times lower than the FLAME-GTA, 12 times lower than our inventory). Ars et al. [52] also find that engineered waterways like the Keating Channel may be a source of methane emissions missing in bottom-up inventories.

We also compare the oil/gas emissions in our inventory to a bottom-up lifecycle analysis from the Oil-Climate Index (OCI) model [53,54]. The OCI model uses detailed information on oil/gas infrastructure to estimate greenhouse gas emissions associated with upstream activities. Methane emissions from a subset of oil/gas fields in Canada (representing 36% of production) were estimated using the OCI model with an assumption of 85% flare efficiency and emissions were then scaled up based on production statistics for the remaining fields to estimate national fugitive oil/gas emissions of 1.9 Tg a^{-1} for 2015, slightly higher than the 2020 NIR estimate of 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% of emissions in our inventory as given by the NIR.

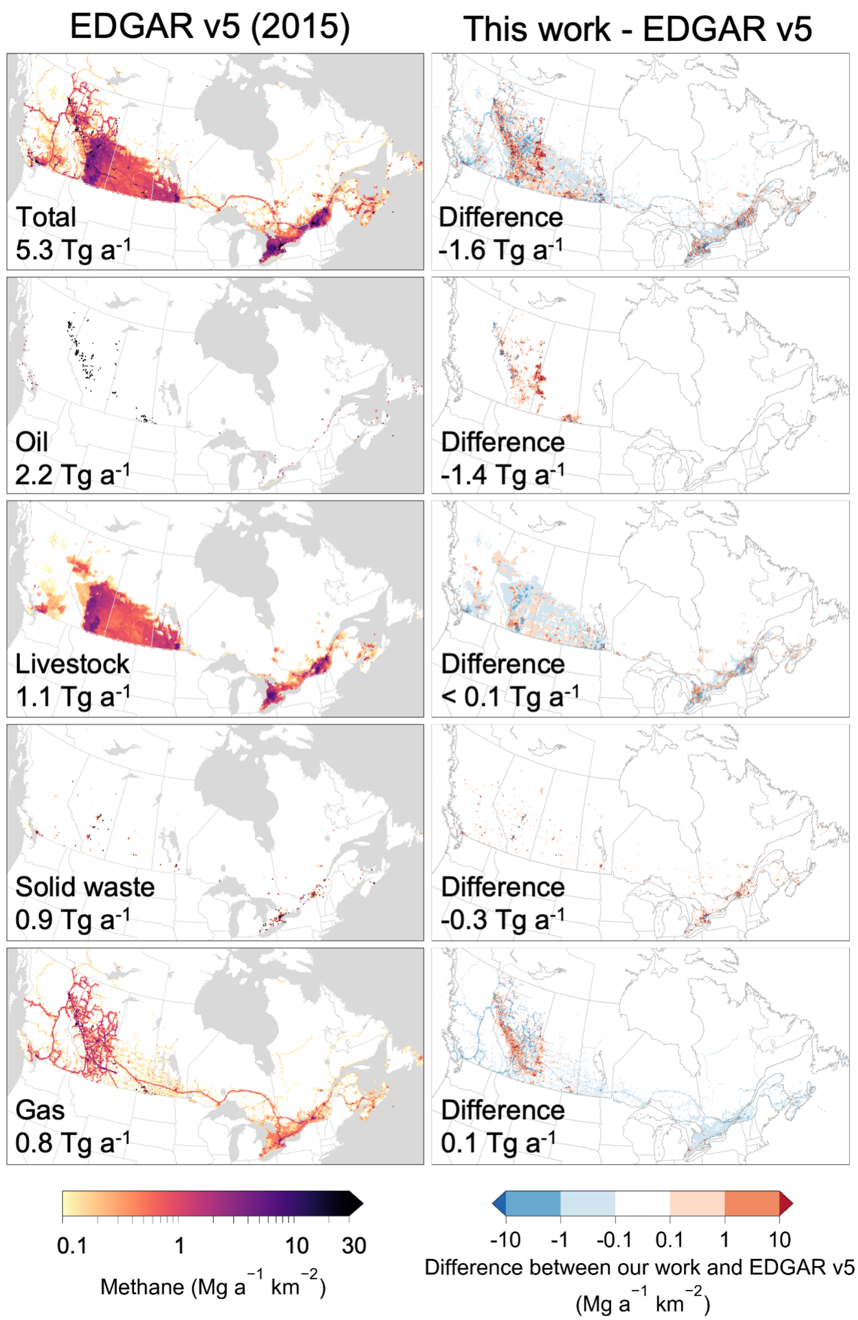

Figure 5. Comparison of Canada's anthropogenic methane emissions in our spatially explicit version of Canada's 2020 National Inventory Report (NIR) to the EDGAR v5 inventory, both on the same 0.1° x 0.1° grid. The left panels are the EDGAR v5 emissions in 2015 (with national totals inset), which can be compared to our emissions in 2018 in figure 2 and figure 3. The right panels show the differences between the two (with national differences inset). Only major sectors are shown.

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 for a gas development region in northeastern British Columbia, which is part of the Montney formation and accounts for about half of British Columbia's gas production.

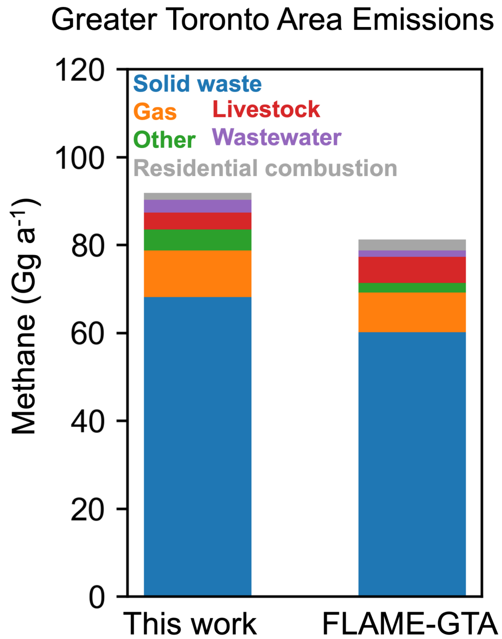

Figure 6. Methane emissions for the Greater Toronto Area in the FLAME-GTA inventory (2016) [51] and in our work (2018) sampled over the same domain. Sectors match those defined in table 1 with the exception that we use gas emissions as defined in table 2.

They estimate emissions of 112 Gg a^{-1}, which is higher than British Columbia's total emissions in the NIR (78 Gg a^{-1} in 2015). Our oil/gas emissions for the Montney region (which we approximate as 55.5 to 57.5 N, 120 to 122.5 W) are 67 Gg a^{-1}.

Johnson et al. [13] estimated methane emissions for two oil/gas production regions in central Alberta based on airborne measurements in 2016. For the Red Deer region, which is characterized primarily by gas wells, their emission rate was 3.1 t h^{-1} while for the Lloydminster region, which is characterized by heavy oil wells, the emission rate was 24.5 t h^{-1}. A separate ground-based field study by Zavala-Araiza et al. [55] in 2016 estimated an emission rate of 4.8 t h^{-1} for the same Red Deer region. Our inventory estimates an oil/gas emission rate of 3.5 t h^{-1} for the Red Deer region (52.3 to 52.9 N, 114.1 to 114.7 W) and 4 t h^{-1} for the Lloydminster region (53.4 to 54.1 N, 110.2 to 110.8 W). 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 venting emissions from cold oil production.

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 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 values 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 [10,56]. Desjardins et al. [57] 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 as represented at 0.5º x 0.5º resolution in the mean of the WetCHARTs inventory ensemble version 1.2.1 [28], and our anthropogenic inventory spatially averaged to the same resolution. The WetCHARTs inventory, described in detail by Bloom et al. [28], is commonly used as a prior estimate of wetland methane emissions in inverse modeling. The national emission from wetlands in the WetCHARTs inventory is 12 Tg a^{-1}, much larger than the anthropogenic source (3.7 Tg a^{-1}). The highest wetland emissions in the WetCHARTs inventory are generally further north and east than the highest regions of anthropogenic emissions, but there is significant spatial overlap in central Alberta, southern Saskatchewan, and southern Manitoba. We find that 1.0 Tg a^{-1} of anthropogenic emissions (27% of national total) are in grid cells where the WetCHARTs ensemble mean indicates more than 30% wetlands contribution to total 0.5º x 0.5º grid cell emissions. There are large discrepancies in the spatial distributions of wetland emissions between different bottom-up inventories [58], further complicating the problem. Inversions of satellite observations and tower measurements have indicated an underestimate of anthropogenic emissions in western Canada [10,11,16,17,19], where there is the most spatial overlap of wetland and anthropogenic emissions.

Wetland emissions in Canada have a large seasonality [59] that could enable separation from anthropogenic emissions in top-down emission estimates. Satellite observations of methane by solar back-scatter 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.

4. Conclusions

We have created a gridded inventory (0.1º x 0.1º resolution) of Canada's 2018 anthropogenic methane emissions as a spatially explicit version of the 2020 National Inventory Report (NIR) submitted to the United Nations Framework Convention on Climate Change (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. Gridded emission files are generated for individual emission subsectors with additional resolution for oil/gas, so that spatial information from the inversions can be attributed to specific emission sources. The inventory is for 2018 but can be adjusted to other years using the year-specific annual data from the NIR.

We allocated NIR subsector emissions to the 0.1º x 0.1º grid using various geospatial datasets including the locations of oil/gas wells and facilities, landfills, coal mines, and wastewater treatment facilities, incorporating facility-specific emissions as reported in Canada's Greenhouse Gas Reporting Program (GHGRP). 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. Oil/gas emissions are mainly from production in western Canada and show substantial regional overlap with livestock emissions. We identified 11 hotspots with emissions greater than 1 t h^{-1} (9 Gg a^{-1}) on the 0.1° x 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.

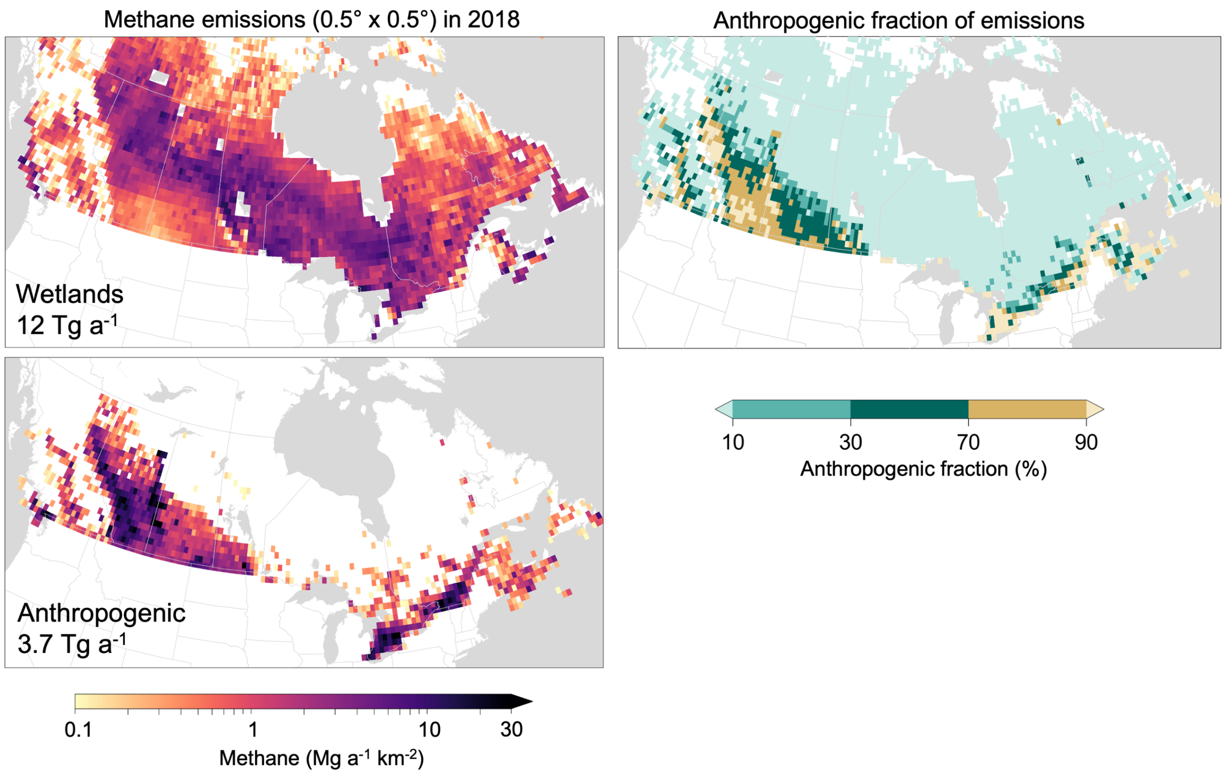

Figure 7. Wetland and anthropogenic methane emissions in Canada (2018). The top left panel shows the mean wetland emissions from the WetCHARTs ensemble produced on a 0.5° x 0.5° grid [28], and the bottom left panel shows our anthropogenic emission inventory averaged over the same grid. The right panel shows the anthropogenic fractions of total methane emissions in the 0.5° x 0.5° grid cells.

Total national emissions in our inventory, as reported in the 2020 NIR, are lower than the EDGAR v5 global inventory, particularly for the oil/gas sector. EDGAR has more localized emissions on the 0.1° x 0.1° grid with 49% of its total emissions in grid cells with emissions greater than 1 t h^{-1}. Our inventory shows agreement with the FLAME-GTA inventory for Toronto's methane emissions. 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 files for 2018 methane emissions, including an emission grid for each sector/subsector/source type of table 1 and table 2, are available at the following URL/DOI: [add citation].

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