If It Matters, Measure It: A Review of Methane Sources and Mitigation Policy in Canada

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Abstract

Methane, a potent greenhouse gas, is critically under-regulated and overlooked by policymakers in Canada. In this paper, we seek to close the science-policy knowledge gap by reviewing the sources of methane emissions in Canada, policies in place, and mitigation options for each source. We show three primary sectors account for 96 per cent of Canada's methane emissions: oil and gas, agriculture, and waste. The oil and gas sector is the largest contributor to national methane emissions, as well as the only sector with methane regulations and a methane reduction target. Livestock is the largest single source of methane emissions in Canada while the agriculture sector as a whole is the largest source of unregulated and unpriced methane in Canada. Our review reveals that emissions measurement challenges hinder methane emissions management for all sectors. Due largely to these challenges, most of Canada's methane emissions are unregulated and policy options are limited. Broadly, options include command and control regulation or financial penalties for oil and gas methane, incentives for farm-level reductions in agricultural methane, and upstream or downstream waste recovery. Better methane management is crucial to achieving Canada's 2030 and 2050 emissions reduction goals. Key short-term policy actions are improving and standardizing current emissions estimates and identifying unregulated sources. Longer-term actions require further study of cost-effective regulatory options across all sources, to support stricter regulations or well-defined market-based approaches with measurable outcomes.

Key words: methane emissions, mitigation options, emissions regulation

JEL Codes: Q15, Q52, Q54, Q58

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Introduction

The *Pan-Canadian Framework on Clean Growth and Climate Change* (PCF), released in 2016, outlines Canada's joint federal-provincial plan for reducing greenhouse gas emissions and meeting its international climate obligations. The PCF was updated in late 2020 with a wholly federal plan, *A Healthy Environment and a Healthy Economy* (HEHE). Actions outlined in the PCF and HEHE focus primarily on carbon dioxide (CO_2), the most prominent greenhouse gas and the standardized unit of measurement for all greenhouse gases. Less discussed are the non-CO_2 greenhouse gases, which in 2019 accounted for 20 per cent (147,855 kt CO_2e) of Canada's reported greenhouse gas emissions.[1] Among these, methane (CH_4) is the largest contributor in terms of global warming potential. Canada's official greenhouse gas inventory estimates methane emissions of 3,910 kt in 2019. This equates to carbon dioxide equivalent (CO_2e) emissions of 97,761 kt or 13 per cent of Canada's total greenhouse gas emissions.[2] As a matter of perspective, this is greater than Canada's greenhouse gas emissions from the electricity sector (61,000 kt), the oil sands (83,000 kt) and individual passenger transport (89,000 kt) (Environment and Climate Change Canada 2021a).

The Government of Canada's primary action to address methane emissions is a commitment to reduce emissions from the oil and gas sector by 40 to 45 per cent by 2025, along with a proposal to add 2030 and 2035 targets (Environment and Climate Change Canada 2016a, 2020a). Secondary actions include the carbon price, which applies to methane emissions from the incomplete combustion of fossil fuels, as well as a commitment to identify opportunities to increase the diversion of organic waste from landfills and the generation of renewable fuels and bioproducts. The HEHE plan additionally proposes to establish methane regulations for "large landfills" (Environment and Climate Change Canada 2020a).

Commitments outlined in the PCF and HEHE appear to target up to seventy per cent of Canada's methane emissions. This proportion is uncertain, however, as methane emissions are particularly difficult to measure and estimation methods tend to have large margins of error. Notably, the Government of Canada does not address the challenge of measuring methane emissions — and the need to establish more reliable baselines — in the PCF nor any subsequent regulations or policy documents targeting methane, including HEHE.

In this paper, we summarise and describe sources of methane emissions in Canada. Our goal is to identify where methane emissions come from, the challenges in measuring methane emissions and the opportunities for mitigation. We also highlight the sources of methane emissions that are currently subject to provincial or national emissions reduction policies and identify regulatory gaps where additional policies may be appropriate. We draw on extant literature, summarising key points and provide a focussed look at methane emissions from a policy perspective, considering sources of emissions, mitigation options and regulatory challenges. We provide the first comprehensive assessment of methane sources and policy coverage in Canada.

There are three sectors that account for the majority (96 per cent) of Canada's methane emissions: oil and gas, agriculture, and waste. At the sector-level, oil and gas is the largest contributor to national methane emissions, as well as the only sector with an explicit emissions reduction target. There are opportunities

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[1] According to Canada's official inventory, the country's total greenhouse gas emissions in 2019 were 730,245 kilotonnes (kt) of carbon dioxide equivalent, CO_2e (Environment and Climate Change Canada 2021a). The direct "carbon dioxide" or "CO_2" component of this total was 582,390 kt, accounting for 80 per cent of Canada's total greenhouse gas emissions.

[2] International conversion rates for methane to carbon dioxide are contested and, consequently, are regularly re-evaluated and updated in the Intergovernmental Panel on Climate Change Assessment Reports. The current recommended rate for methane reporting purposes is 25 and is from the fourth assessment report, released in 2012 (UNFCCC Secretariat 2013). A more detailed explanation of conversion rates is provided in the next section.

for significant emissions reductions, as a large share of methane releases in oil and gas are avoidable through improved processes, and leak identification and repair. As a result, most existing research on methane emissions policy focusses on oil and gas. This literature includes the accuracy of Canada's current methane emissions estimates (Johnson et al. 2016; Atherton et al. 2017; Johnson et al. 2017; Werring 2018; Zavala-Araiza et al. 2018; Chan et al. 2020; MacKay et al. 2021); policy implications stemming from measurement difficulties and the lack of a reliable baseline estimate (Jordaan and Konschnik 2019; O'Connell et al. 2019; Schiffner, Kecinski, and Mohapatra 2021); options for methane abatement (ICF International 2015; Munnings and Krupnick 2017; Gorski et al. 2018; Tyner and Johnson 2018); and evaluation of provincial and federal methane regulations and equivalency agreements (Gorski 2019; Johnson and Tyner 2020a).

In contrast, research on methane emissions policy for the agriculture and waste sectors is limited, particularly in Canada. Existing sector-specific research on methane emissions is generally technical in nature, focusing primarily on measurement methods or abatement options (Basarab et al. 2013; Vu, Ng, and Richter 2017; Desjardins et al. 2018; Duthie et al. 2018; Worden and Hailu 2020). Policy-focussed research has tended to treat methane emissions as one component of a broader discussion of the overall sustainability and clean growth opportunities for agriculture and solid waste management systems (Ragan et al. 2018; Yildirim, Bilyea, and Buckingham 2019).

The remainder of this paper proceeds as follows. We start with a brief primer on methane and an overview of Canada's methane emissions from anthropogenic sources. We summarise methane's (estimated) contribution to Canada's total greenhouse gas emissions profile and the shares of methane emissions across provinces. Next, we briefly discuss the uncertainty around current methane emissions estimates, and then provide a sectoral analysis: describing sources of methane within each sector and opportunities for methane reduction. We identify key existing policies or programs that encourage methane emissions reductions. We conclude with identifying future opportunities for methane emissions mitigation in Canada.

A Brief Primer on Methane

Methane (CH_4) is a colourless, odourless and tasteless gas. Methane emissions can be attributed to three primary sources. The first source is direct releases of natural gas — of which methane is a key component — to the atmosphere. Methane from direct releases of natural gas is classified as either venting or fugitive emissions. Venting emissions are natural gas releases that are deliberate and controlled. For example, venting is a common operational feature of equipment, such as pneumatic devices and compressors, that run on natural gas. Fugitive emissions, in contrast, are a result of accidental releases of natural gas. As natural gas can form in its own reservoir, alongside crude oil, and in coal seams, it is common for both venting and fugitive natural gas releases to occur as part of the natural gas, coal and oil extraction process. Emissions can also occur along all segments of the upstream, mid-stream and downstream oil and gas supply chain, as well as from industrial processes that rely on natural gas as an input. Direct releases of natural gas are the largest source of methane emissions in Canada.

The second source of methane emissions in Canada are chemical reactions that release methane as a by-product. The most common of these is the incomplete hydrocarbon combustion: when hydrocarbons are combusted in an environment that has insufficient oxygen. Complete hydrocarbon combustion results in the release of only water vapour and carbon dioxide; incomplete combustion can result in numerous by-products, one of which is methane. In Canada, the two hydrocarbons that generate most of the methane from incomplete combustion are residential biomass and raw natural gas used onsite by producers in the upstream oil and gas sector.

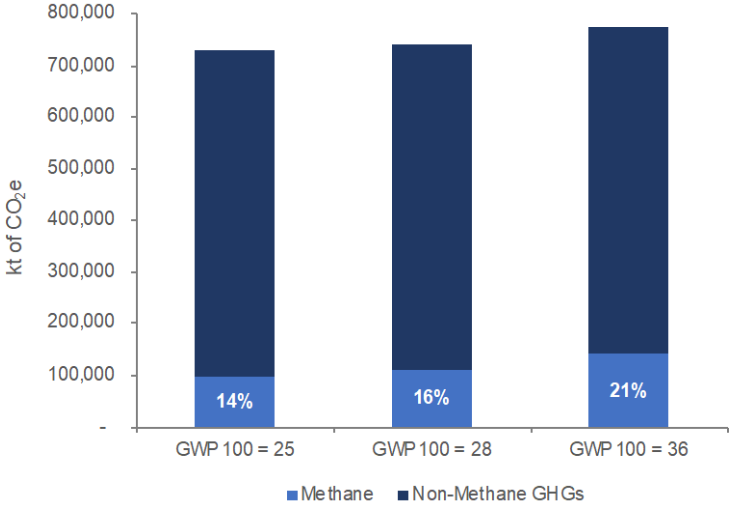
The final major source of methane is from a type of microorganism classified as methanogenic archaea, or, more simply, methanogens. Methanogens generate methane as a metabolic byproduct when breaking down organic material in an anaerobic environment (that is, an environment without oxygen). The two most common processes that result in methanogenic activity are the degradation of organic landfill waste and digestion of food by ruminant animals. In the former process, methane is emitted to the atmosphere after migrating to the landfill surface; in the latter case methane is primarily emitted through ruminant animals' belching. The amount of methane generated is dependent on the specific characteristics of the organic material being broken down, as well as the conditions under which it decomposes. While optimal conditions for methanogenic activity will vary across subgroups of methanogens, two environmental conditions that typically increase activity — and thereby methane generation — are higher temperatures and moisture. Also key is that oxygen suppresses the activity of methanogens. Accordingly, methane generation will sharply decline when organic material is broken down in an aerobic environment (that is, in the presence of oxygen).

As with all of the non-CO_2 greenhouse gases, Canada's greenhouse gas inventory reports methane emissions in tonnes of CO_2e. Canada converts methane into CO_2e using a "global warming potential" (GWP) factor. The GWP factor approximates how many tonnes of CO_2 will result in the same global warming effect, over a specific period, as one tonne of methane. The use of CO_2e creates a common unit of measurement for all greenhouse gases and facilitates comparison of the relative impact of these gases within Canada's overall emissions profile.

Methane has a relatively short atmospheric life of approximately 12 years (IPCC 2013). Significantly, however, it has a much more powerful warming effect than carbon dioxide over this short period. The fifth assessment report from the Intergovernmental Panel on Climate Change (IPCC), published in 2014, estimates the 20-year GWP for methane between 84 and 87 and the 100-year GWP between 28 and 36 (IPCC 2013). This means that, over two decades, the warming impact of one tonne of methane is 84 to 87 times greater than one tonne of CO_2. Over one century, the warming impact of methane falls to between 28 and 36 times greater than one tonne of CO_2. The reduction in GWP over the 100-year time period reflects the short lifespan of methane in relation to CO_2.

International reporting guidelines for greenhouse gas emissions under the United Nations Framework Convention on Climate Change (UNFCCC) recommend converting methane to CO_2e using a 100-year GWP. The most recent version of these guidelines recommends a 100-year GWP for methane of 25, based on the fourth assessment report of the IPCC, instead of the more recent fifth assessment report (UNFCCC Secretariat 2013). Canada follows these UNFCCC guidelines when preparing its annual National Inventory Report (NIR), Canada's only source for a comprehensive estimate of national and provincial methane emissions. Using the GWPs from the fourth assessment report results in significant underestimation compared to the fifth assessment report. When the more recent 100-year GWPs (between 28 and 36) are applied, Canada's methane emissions estimate increases by 11,700 to 43,000 kt CO_2e relative to the current NIR estimates (Figure 1). This corresponds to an increase in Canada's total greenhouse gas emissions estimate of between 1.6 and 5.9 per cent. Also significant is that methane's share of total emissions in Canada would increase by up to one-third (rising from 13 per cent with a 100-year GWP of 25 to 18 per cent with a 100-year GWP of 36).

Figure 1: Effect of 100-year Methane GWP Assumptions on Canada's Emissions Estimates



Source: Authors' calculations using data from Environment and Climate Change Canada (2021a).

An Overview of Methane Emissions in Canada

Relative to Canada's total greenhouse gas emissions, methane emissions in Canada have remained relatively constant over time (Figure 2).[3] Methane emissions in 1990 were 93,300 kt CO_2e (Environment and Climate Change Canada 2021a). They rose to a peak of 121,000 kt CO_2e in 2000 and have since been largely declining, reaching 97,800 kt CO_2e in 2018. Methane's share of Canada's total greenhouse gas emissions has declined from a high of nearly 18 per cent in the mid-1990s to 13 per cent in 2018. This declining share is driven primarily by rising greenhouse gas emissions in sectors that do not generate significant amounts of methane emissions. In particular, between 1990 and 2018 there have been substantial increases in carbon dioxide emissions from the oil sands sector and from passenger and freight transport.

As Canada's methane emissions reporting follows UNFCCC guidelines, IPCC guidelines determine emissions categories. These guidelines specify four main top-level GHG categories: Energy; Industrial Processes and Product Use (IPPU); Agriculture; and Waste.[4] We report methane emissions according to each of these categories in Appendix A, including as shares of category emissions, shares of total methane emissions, and shares of total GHG emissions.

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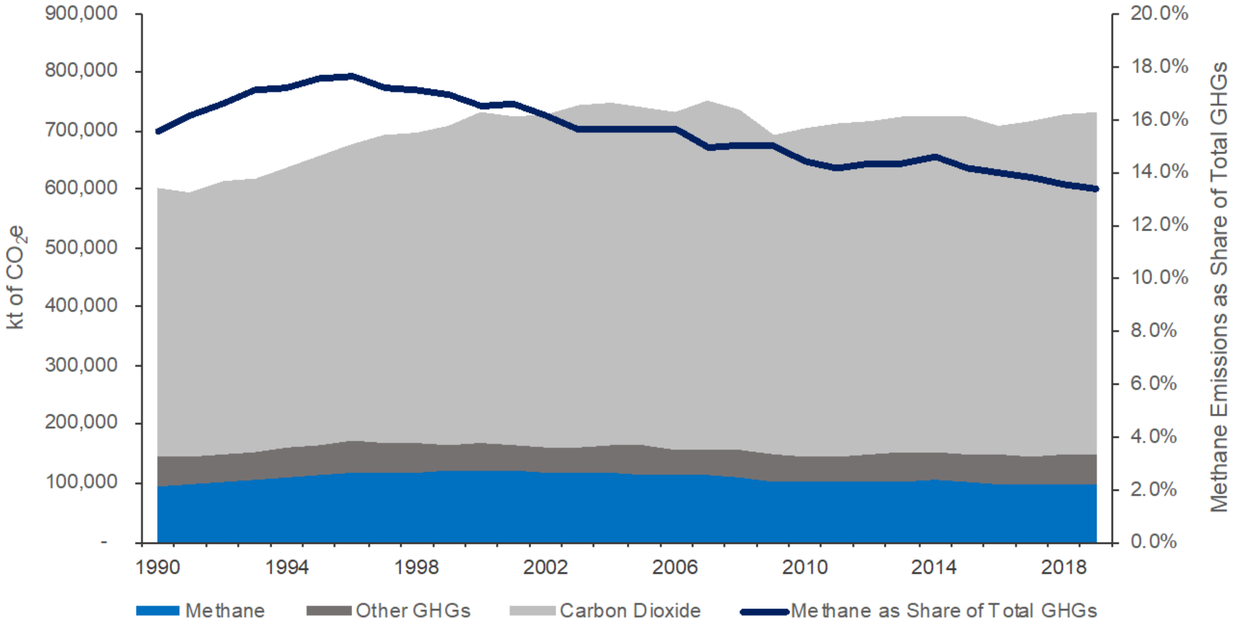
[3] Throughout this section, we reference methane emissions as reported in the National Inventory Report. That is, the CO_2e values have been converted from tonnes of CH_4 using a 100-year GWP of 25.

[4] The fifth IPCC emissions category is Land Use, Land Use Change and Forestry (LULUCF). Under UNFCCC guidelines, countries are required to report LULUCF emissions at the national level only, and the LULUCF emissions total is not included in the national inventory total of greenhouse gas emissions. As Canada's estimated methane emissions in the LULUCF category are additionally quite small compared to other categories (584 kt CO_2e) we have opted not to include them in the discussion.

Figure 2: Canada's Historical Greenhouse Gas and Methane Emissions (CO_2e)

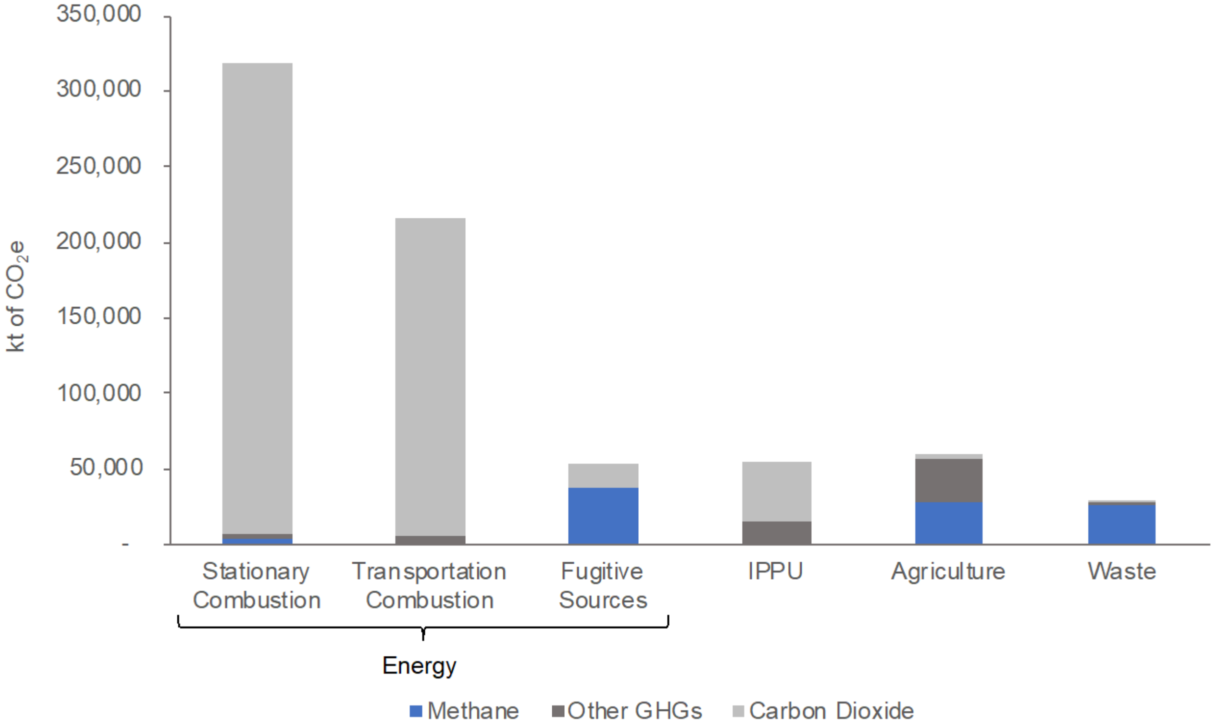


Source: Authors' calculations using data from Environment and Climate Change Canada (2021a)

The Energy category is the largest source of greenhouse gas emissions and encompasses three primary subcategories: stationary combustion emissions, transportation combustion emissions and fugitive sources (from the oil and gas sector and coal mining). Stationary and transportation combustion emissions are primarily carbon dioxide (98 per cent), with only a small proportion (1.3 per cent) of methane releases from incomplete combustion (Figure 3). Methane from incomplete combustion is mainly from the oil and gas sector and the residential sector (Environment and Climate Change Canada 2021a). Methane emissions in the oil and gas sector come from high producer use of raw natural gas; residential methane emissions are primarily attributable to biomass burning in wood stoves and fireplaces. Fugitive sources are unintentional or waste fossil fuel emissions from coal mining and the entire oil and natural gas supply chains. The IPCC guidelines further divide fugitive sources into emissions from controlled processes (flaring and venting) and uncontrolled processes (unintentional emissions from coal mining and the oil and natural gas sector). Methane emissions from flaring are due to incomplete combustion, while in the other subcategories they are from direct releases to the atmosphere. As a whole, the fugitive sources category is 70 per cent methane emissions.

Together, incomplete combustion and fugitive sources in the oil and gas sector account for 40 per cent (38,900 kt CO_2e) of national methane emissions (Figure 4); the oil and gas sector is the largest contributor to Canada's total methane emissions. The largest sources of methane within the oil and gas sector are venting (19 per cent of national emissions/18,945 kt CO_2e) and uncontrolled fugitive emissions from natural gas production (12 per cent/11,966 kt CO_2e).

Figure 3: Greenhouse Gas and Methane Emissions by IPCC Reporting Category (2019)

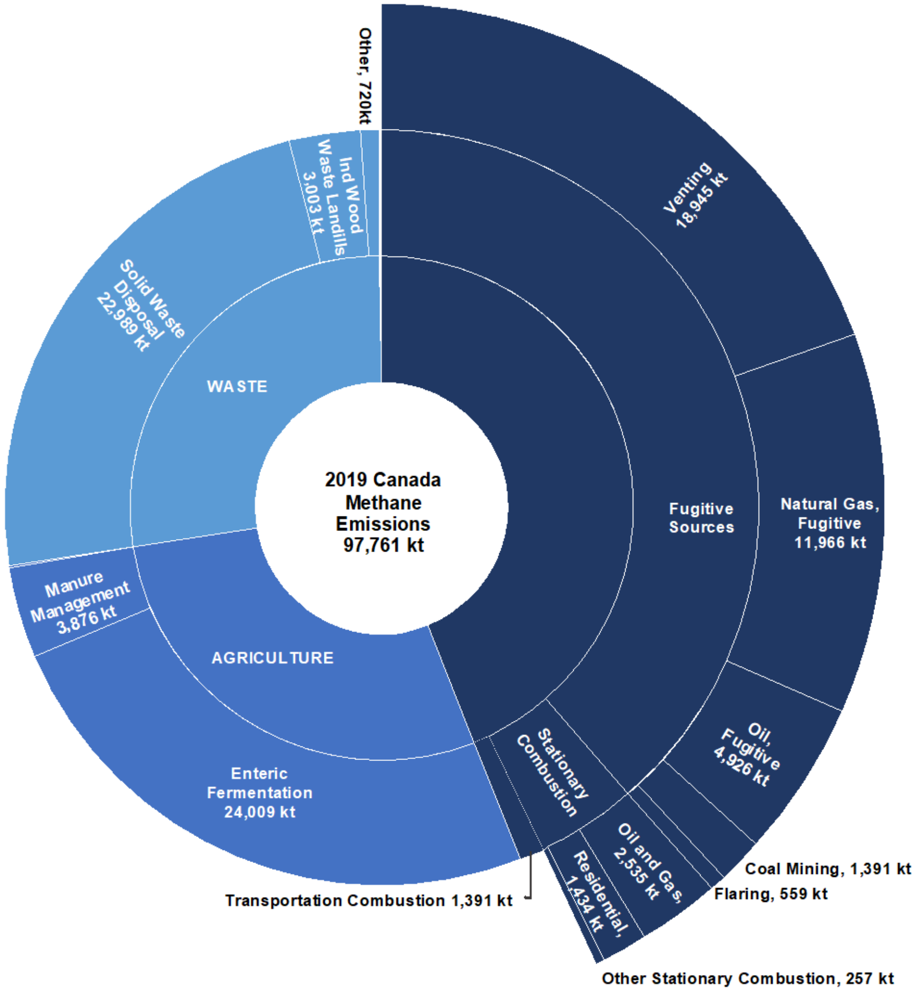


Source: Authors' calculations using data from Environment and Climate Change Canada (2021a)

The agriculture sector accounts for 29 per cent of national methane emissions, almost entirely through non-combustion emissions. Enteric fermentation, which captures the methane emissions produced by methanogens as a byproduct of cattle and other ruminant livestock's digestion, is the largest single source of methane emissions in Canada, accounting for 25 per cent (24,009 kt CO_2e) of national emissions. The waste sector accounts for 27 per cent (16,588 kt CO_2e) of national emissions with most of that total attributable to solid waste disposal (24 per cent/22,989 kt CO_2e) or, more specifically, methanogens' decomposition of solid organic waste. Also of note is that methane emissions are highly prevalent in both the agriculture and waste sectors where they account for 28 and 97 per cent of total sector emissions respectively.

In the IPPU category methane emissions are minimal, accounting for only 0.1 per cent of total category emissions. Most methane emissions in this category are attributable to chemical reactions from petrochemical product production. Of note, however, is that any industrial facility that uses natural gas as a fuel source is susceptible to methane emissions as a result of leaks (fugitive emissions) and incomplete combustion. While an estimate of methane emissions from incomplete combustion is included in the energy sector category, the IPCC does not include fugitive emissions in its IPPU category. This suggests IPPU methane emissions may be an underestimate. For example, studying the U.S. fertilizer industry, Zhou et al (2019) use airborne measurements to estimate an industry loss rate for natural gas of 0.34 per cent, which corresponds to annual industry methane emissions of 28 kt. In comparison, the U.S. fertilizer industry reported annual methane emissions of only 0.2 kt annually to the U.S. EPA (Zhou et al. 2019).

Figure 4: Canadian Methane Emissions (kt of CO_2e) by IPCC Subcategory (2019)



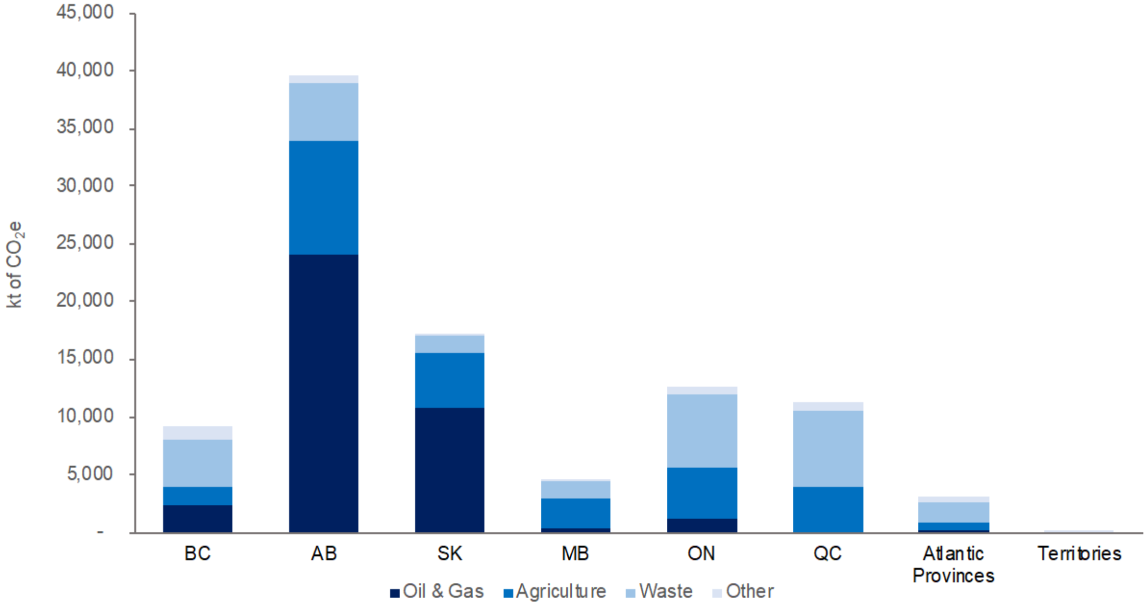
Source: Authors' calculations using data from Environment and Climate Change Canada (2021a)

Note: The "other" subcategory in the waste category includes methane emissions from biological treatment of solid waste (187 kt CO_2e), wastewater treatment and discharge (532 kt CO_2e) and waste incineration and open burning (1 kt CO_2e). The "other" subcategory in the stationary combustion category includes Public Electricity and Heat Production (158 kt CO_2e), Petroleum Refining Industries (8 kt CO_2e), Mining (3 kt CO_2e), Manufacturing Industries (64 kt CO_2e), Construction (0.6 kt CO_2e), Commercial and Institutional Buildings (21 kt CO_2e) and Agriculture and Forestry (2 kt CO_2e). Last, the transport category is further subdivided into Aviation (5 kt CO_2e), Road Transportation (245 kt CO_2e), Railways (10 kt CO_2e), Marine (10 kt CO_2e) and Other Transportation (off-road vehicles and pipelines) (708 kt CO_2e). Not visible in the figure due to small quantities are methane emissions in the IPPU category (137 kt CO_2e) and methane emissions from the agriculture subcategory of field burning of agricultural residues (37 kt CO_2e). Two additional agriculture subcategories — agricultural soils and liming, urea application and other carbon-containing fertilizers — have zero recorded methane emissions.

The last piece we consider is how methane emissions differ across provinces (Figure 5). Unsurprisingly, methane emissions are highest in Alberta (39,622 kt CO_2e), which accounts for the majority of Canada's oil and gas production and is home to the largest proportion (approximately 40 per cent) of Canada's cattle population (Canada Energy Regulator 2020; Statistics Canada 2020e). Second in methane emissions is Saskatchewan (17,140 kt CO_2e), which correspondingly is second in Canada for both oil production and cattle population. Oil and gas and agriculture account for over 85 per cent of methane emissions in both provinces, with the remaining share of methane emissions primarily attributable to the waste sector.

Third and fourth for methane emissions are Ontario (12,704 kt CO_2e) and Quebec (11,318 kt CO_2e) respectively, where emissions are primarily attributable to the waste and agriculture sectors. Ontario additionally has 10 per cent of its methane emissions from the oil and gas sector. As actual oil and natural gas production in the province is negligible, this is most likely a result of fugitive emissions from the province's network of natural gas transmission and distribution pipelines.

Figure 5: Methane Emissions by Province and Sector (2019)



Source: Authors' calculations using data from Environment and Climate Change Canada (Environment and Climate Change Canada 2021a) .

British Columbia's methane emissions (9,244 kt CO_2e) are fifth highest among the provinces; the waste sector is its largest source. This is somewhat unexpected as British Columbia is Canada's second largest producer of natural gas, accounting for nearly one-third of production in 2019 (Canada Energy Regulator 2020). Despite this, the province accounted for only 6.5 per cent of fugitive emissions from natural gas production (and only 5 per cent of total Canadian oil-and-gas-sector methane emissions). In comparison, Alberta accounted for 65 per cent of natural gas production in 2018 and 63 per cent of fugitive methane emissions from natural gas production, while Saskatchewan accounted for only 2 per cent of production and 21 per cent of fugitive natural gas methane emissions. Much of this discrepancy can likely be explained by lower use of natural-gas-driven pneumatic devices at British Columbian production sites (Robinson et al. n.d.). Also of note is higher volumes of natural gas — and correspondingly fugitive emissions — in transmission pipelines that start in Alberta and run through Saskatchewan, delivering natural gas to Eastern Canada and the United States. Fugitive natural gas emissions from distribution pipelines are also likely weighted towards Ontario and Alberta, which have the highest household use of natural gas as an energy source (Natural Resources Canada 2018).

Manitoba (4,438 kt CO_2e) and the Atlantic provinces (3,170 kt CO_2e) have the lowest levels of methane emissions. In Manitoba, the agriculture sector accounts for over 60 per cent of methane emissions, with a small amount of additional emissions from the waste sector. In the Atlantic provinces the largest source of methane emissions is the waste sector, with small amounts also attributable to agriculture and the residential sector. Last, at only 122 kt CO_2e, methane emissions in the territories are negligible.

Uncertainty in Methane Emissions Estimates

Methane can be difficult to measure as the three sources identified earlier — direct releases of natural gas, chemical reactions and methanogenic activity — are challenging to track and quantify. Typically, there are two approaches used for estimating methane emissions: top-down or bottom-up (National Academies of Sciences Engineering and Medicine 2018).

The top-down approach starts by taking atmospheric measurements of methane concentrations. These concentrations are inputs to an atmospheric transport model that attributes them to a location and source. While top-down models can provide accurate and complete measurements of methane concentrations where the sampling occurs, it can be difficult to attribute these emissions to a specific point source. This is particularly a challenge in geographic areas with overlapping sources of methane. On ranch lands in Alberta and Saskatchewan, for example, it is common to find cattle, which are significant emitters of methane, grazing in close proximity to oil and gas wells.

The bottom-up approach starts with sampling, measurements and modelling of methane emissions at individual point sources. This information is used to calculate an emission factor, which approximates the average emissions per individual point source. Total regional emissions are then estimated by multiplying each emission factor by an activity factor that approximates the total number of individual point sources in a region.

The approach of estimating emissions by multiplying an emission factor by an activity factor is the most common method used in the NIR to estimate greenhouse gas emissions of all kinds. In line with IPCC guidance, activity factors are calculated using Canada-specific methodologies and emission factors are calculated using one of the three IPCC "tiers"[5] of methodologies, which range in complexity and country-specificity.

For CO_2 combustion emissions, the most common source of greenhouse gas emissions, estimating emissions with an activity factor and an emission factor is a relatively straightforward process: the activity factor is quantity of fuel consumed and the emission factor is quantity of CO_2 per unit of fuel. While the emission factor will vary with specific characteristics of the fuel and the combustion engine, both measures can be estimated with reasonable precision. The NIR offers insight on the precision of its emissions estimates through its uncertainty assessment, which provides the range in which repeated measurements of emissions are likely to fall. For the six largest sources of CO_2 combustion emissions in the 2019 NIR, the relative uncertainties range from 1.1 to 5.0 per cent (Figure 6).

For methane emissions, in contrast, there is much more uncertainty around the precision of the NIR estimates. The six largest methane sources in the 2019 NIR had relative uncertainty estimates ranging from 6 to 190 per cent. Further, despite emissions from methane sources being much smaller than combustion emissions, the absolute uncertainty — that is, the full range of emissions in which repeated measurements are likely to fall — is typically much larger. For three of the six methane emissions categories — municipal solid waste landfills, industrial wood waste landfills and enteric fermentation — the absolute uncertainty exceeded all six of the largest sources of combustion emissions. The NIR identifies these same three methane emissions sources as being the first, third and fourth largest

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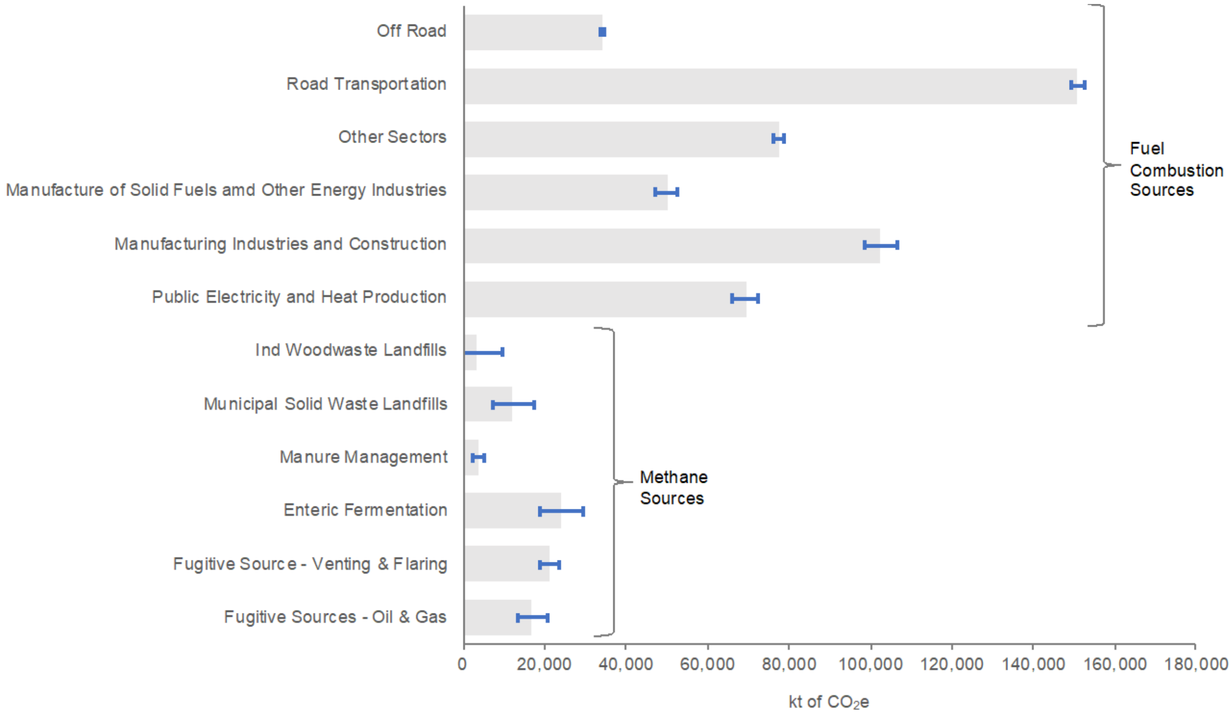
[5] A tier represents the level of methodological complexity used in calculating estimated emission factors, with three tiers used in the 2006 IPCC Guidelines (as well as the 2019 Refinement to these guidelines). Tier 1 is the most basic IPCC method and does not incorporate any country-specific data in the calculation of the emission factor. Tier 3 is the most complex and requires the most data, while Tier 2 incorporates some country-specific data and some IPCC default data.

contributors to the overall uncertainty in the estimate of Canada's total greenhouse gas emissions, when excluding land use, land use change and forestry (LULUCF) emissions.[6]

Figure 6: Uncertainty in NIR Emissions Estimates



Source: Authors' calculations using data from Environment and Climate Change Canada (2021d).

Note: The x-axis reports the total emissions estimates from the NIR by sector, and the blue error bars show the range of uncertainty. The NIR notes that uncertainty ranges are not a measure of accuracy (how close the emissions estimates are to their true value) but rather precision (the range of estimates that is likely to result from repeated measurements). For each emissions category, the NIR provides an uncertainty estimate for the activity data, the emission factor and the overall emissions estimate. For most emissions categories, the overall uncertainty is driven predominantly by uncertainty in the emission factor.

Several factors contribute to the high uncertainty in methane emissions estimates. Methane emissions from direct releases of natural gas, for example, are primarily attributable to the oil and gas sector, which tends to be characterized by super emitters: a small number of facilities that are responsible for the majority of emissions (Zavala-Araiza et al. 2015; Zavala-Araiza et al. 2018). Further, emissions are frequently a result of uncontrolled and disparate events — including human error, equipment failure, pipeline ruptures and well blowouts — that may or may not be detected. As methane emissions associated with these events are colourless, odorless and tasteless, they have a high probability of going undetected. These characteristics are in stark contrast to the underlying assumption of the bottom-up estimation approach, which is a static and homogenous relationship between the activity factor and the emission factor.

Methane emissions attributable to methanogens are mostly found in the agriculture sector and the waste sector. The level of these emissions is highly dependent on site-specific environmental conditions; in particular, temperature, moisture and oxygen availability, and the management systems in place at individual farms and landfills. As it is not practical to obtain emission factors at the individual farm- and

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[6] With the inclusion of LULUCF emissions, industrial wood waste landfills drop to the fourth largest contributor and enteric fermentation to fifth. Municipal solid waste landfills are no longer on the list as one of the top five sources of uncertainty.

landfill-level, much of this information will not be captured when estimating emissions using the bottom-up approach. In the waste sector, uncertainty is also introduced by a lack of detailed data on the volumes and types of waste sent to landfill each year.

Last, it is worth noting the uncertainty values are not intended to reflect accuracy of the NIR's estimates, which as stated by the NIR, ". . . can only be quantified by measuring departure from the truth" (Environment and Climate Change Canada 2021d). The true value of methane emissions is best determined through top-down measurements of atmospheric concentrations of methane emissions (subject to the qualifications noted at the start of this section). As the NIR does not include information from top-down measurements in its estimates, an assessment of their likely accuracy requires turning to other sources.

There are several studies of the oil and gas sector that compare top-down estimates of methane emissions to inventory estimates (both the NIR and provincial inventories). The authors consistently find that inventory estimates of methane emissions are substantially less than top-down measurements at the provincial level. The range of estimated discrepancies is large, however, varying from 25 to 50 per cent (Johnson et al. 2017), to more than 200 per cent (Atherton et al. 2017; Chan et al. 2020).

We have not identified any research that compares provincial-level inventory estimates of methane emissions to top-down measurements for the agriculture and waste sectors. A few papers compare regional top-down measurements to bottom-up estimates derived by the authors following IPCC methodologies. Research on the agriculture sector generally finds estimates calculated through bottom-up and top-down approaches align reasonably well (Desjardins et al. 2018; Chan et al. 2020). In the waste sector, in contrast, there tends to be a significant discrepancy between top-down and bottom-up estimates (Vu, Ng, and Richter 2017; Chan et al. 2020).

We discuss sector-specific measurement challenges and sources of uncertainty in the NIR emissions estimates in greater detail in Appendix B, which outlines the NIR's estimation methodology for methane emissions from the oil and gas, agriculture and waste sectors. Below, we discuss the implications of these measurement challenges and sources of uncertainty on methane mitigation policy for each sector.

Sector-Specific Sources and Mitigation Opportunities for Methane Emissions

Oil and Gas

Sources

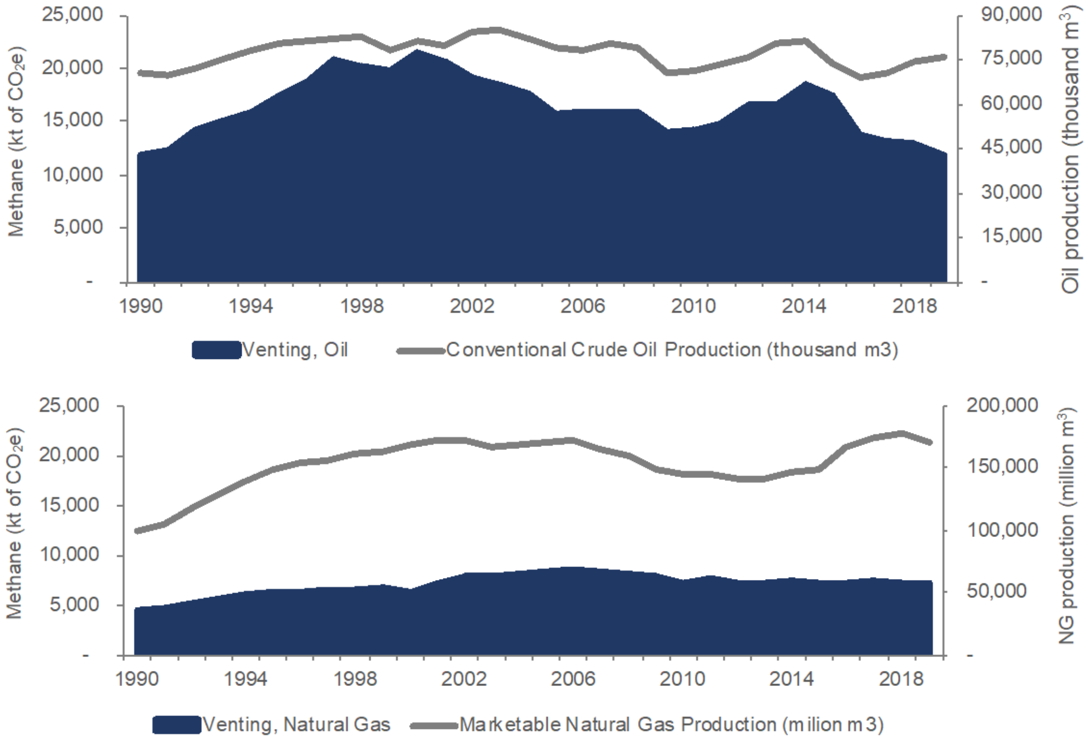
The oil and gas sector emitted 39,139 kt CO_2e of methane in 2019 (Environment and Climate Change Canada 2021a). The large majority of these emissions are from direct releases of natural gas; specifically venting (18,945 kt CO_2e/48 per cent of total oil and gas methane emissions), unintentional natural gas fugitive emissions (11,966 kt CO_2e/31 per cent), and unintentional oil fugitive emissions (4,926 kt CO_2e/13 per cent). The remaining emissions in the sector come from incomplete combustion attributable to stationary combustion processes and pipelines (2,742 kt CO_2e/7 per cent), and flaring (557 kt CO_2e/1 per cent). As methane emissions from incomplete combustion in the oil and gas sector account for only a minor share of total emissions, we focus on methane from direct releases of natural gas for the remainder of this section.

Venting is used for operational, safety and economic reasons to dispose of excess or waste gases along the entire oil and gas supply chain (including exploration, production, processing, transmission, refining and distribution). In 2019, total venting emissions in Canada (from all greenhouse gases) were 28,459 kt CO_2e, with methane emissions accounting for 67 per cent of this total (Environment and Climate Change Canada 2021a).

The largest source of vented methane emissions is solution (or associated) gas that accompanies conventional oil production.[7] With the recent introduction of methane reduction targets for the oil and gas sector in 2018, producers are facing increasingly stricter limits on solution gas venting in large quantities. However, under specific conditions — mainly if the quantity of solution gas is small enough and it is not economic to capture — then limited venting is allowed. Another significant source of vented emissions in the upstream oil and gas sector is pneumatic devices that run on natural gas and vent small amounts at a specified rate as part of their normal operations. Vented emissions also occur at glycol dehydrators, which remove water vapours from produced natural gas before it enters a pipeline and, in the oil sands, at upgraders and liquid extraction plants.

Methane emissions from venting track relatively closely to natural gas and conventional oil production (Figure 7). This is to a degree by construction, as production is one of the key activity factors in estimating emissions from unreported venting and glycol dehydrator off-gas venting (Environment and Climate Change Canada 2021d). There are, however, two notable divergences. First, venting emissions declined faster than conventional oil production in the early 2000s. Second, since approximately 2015, natural gas and conventional oil production have risen without a corresponding increase in methane emissions.

Figure 7: Venting Methane Emissions from Oil and Natural Gas Production



Source: Authors' calculations using data from Environment and Climate Change Canada (2021b) and Statistics Canada (Statistics Canada 2020a, 2020b, 2020c, 2020d).

Note: We do not include oil sands production as conventional crude production is the primary source of venting emissions from oil production. In 2019, conventional crude oil production accounted for 71 per cent of total venting emissions from oil production (Environment and Climate Change Canada 2021a). The remaining emissions are attributable to oil sands upgrading (33 per cent) and in-situ oil sands production (6 per cent).

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[7] The composition of vented emissions by source is unavailable at the national level. However, in Alberta — which drives the national numbers due to its large share of oil and gas production — solution gas venting accounts for 88 per cent of all reported vented gases (methane and other) from the upstream oil and gas sector (Alberta Energy Regulator 2019).

These divergences are likely from changes in reported venting emissions and coincide with both significant regulatory changes and periods of increasing solution-gas conservation. For example, Alberta released its first directives for solution gas management in 1999 and 2006 (Alberta Energy Regulator 2021). The percentage of solution gas conserved correspondingly rose from an annual average of 93 per cent in the late 1990s to 96.0 per cent in the mid-2000s (Alberta Energy Regulator 2019). In 2015, Alberta announced its intention to achieve a 45 per cent reduction in methane emissions from the oil and gas sector (Government of Alberta 2015). The federal government similarly announced its intent to regulate methane emissions reductions in the oil and gas sector in early 2016 (Environment and Climate Change Canada 2016b).

Similar to venting, unintentional fugitive emissions in the oil and natural gas sector capture direct, non-combusted releases of gas to the atmosphere. What distinguishes these emissions from venting, however, is that they are uncontrolled. Unintentional fugitive emissions occur along the entire gas supply chain, while along the oil supply chain they occur primarily at the production and processing stages.[8] There are multiple sources of these emissions including equipment and pipeline leaks; accidents and equipment failures; evaporative losses from storage tanks; losses during the transfer of liquid products (loading and unloading); and surface-casing vent flows[9] and gas migration[10] from active, inactive and abandoned[11] oil and gas wells. There are two additional fugitive emissions sources in oil sands mining. First, methane trapped in the oil sands ore is emitted from the faces of open-pit mines, and during transport and processing of the mined ore (Johnson et al. 2016). Second, tailings ponds emit methane via methanogens decomposing residual hydrocarbons (Siddique et al. 2012).

As fugitive emissions are almost entirely attributable to direct atmospheric releases of non-combusted natural gas, methane comprises most of this category. In 2018, total unintentional fugitive emissions from oil and natural gas production in Canada were 17,661 kt CO_2e, with methane emissions accounting for 96 per cent of the total (Environment and Climate Change Canada 2021a).

As is the case for venting emissions, unintentional fugitive emissions estimates track fairly closely with production. This is again by virtue of oil and natural gas production being key activity factors in estimating these emissions (Figure 7). A significant exception, however, is a sharp decline in natural gas unintentional fugitive emissions from 1998 to 2002 while production continued to rise. Emissions fell across all subcategories of natural gas fugitive emissions over this period. The sharpest decline was from natural gas transmission and storage, with emissions falling from 5,629 kt of CO_2e annually in 1998 to only 1,169 kt annually in 2002 (Environment and Climate Change Canada 2021b). The cause of this change is unknown, particularly as the length of natural gas transmission pipelines in Canada also increased over this period. The most likely explanation seems to be a change in the source of the emissions estimates over the periods of 1997 to 1999 versus 2000 to 2004.[12]

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[8] Unintentional fugitive emissions are largely limited to the production and processing stages of the oil supply chain as any solution gas that is not vented or flared and remains mixed with the oil following production will be removed at the processing stage. As unintentional fugitive emissions are primarily uncontrolled releases of natural gas, once the solution gas is removed there is limited opportunity for further emissions.

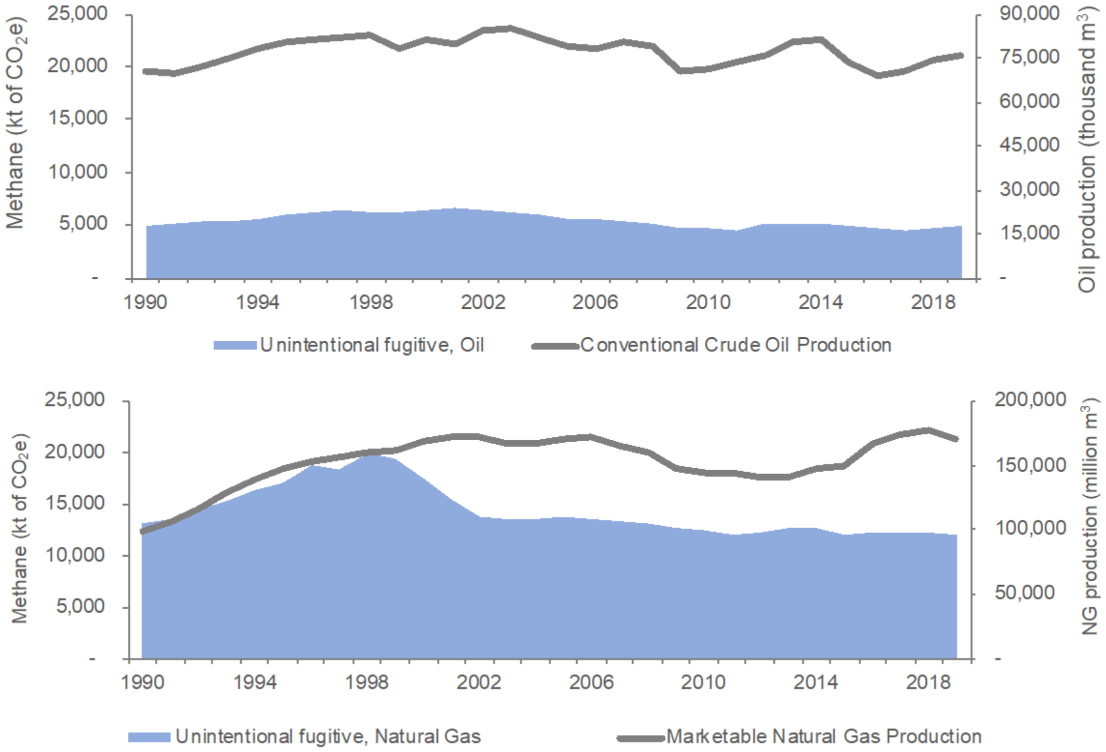
[9] The release of gas, liquid or both from the surface casing of an oil or gas well (Alberta Energy Regulator 2019).

[10] Where gas flows away from the casing of a well and becomes detectable at the surface (Alberta Energy Regulator 2019).

[11] "Abandoned" is the term for wells that reach the end of their productive life; they are generally permanently plugged and the land reclaimed.

[12] Between 1997 and 1999, fugitive emissions from natural gas transmission are estimated based on natural gas transmission pipeline lengths and leakage rates (with leakage rates determined using 1996 emissions data from a Canadian Association of Petroleum Producers report on methane and volatile organic compound emissions from the upstream oil and gas industry). Between 2000 and 2004, fugitive emissions data was provided by the Canadian

Figure 8: Unintentional Fugitive Methane Emissions from Oil and Natural Gas Production



Source: Authors' calculations using data from Environment and Climate Change Canada (2021b) and Statistics Canada (Statistics Canada 2020a, 2020b, 2020c, 2020d).

Mitigation Options

As with most pollutants, the two overarching regulatory options for mitigating methane in the oil and gas sector are financial penalties and command-and-control regulation. Methane emissions from the oil and gas sector are unique in that most methane emissions are from natural gas releases, which is a marketable product with a distinct value. Correspondingly, marginal abatement cost curves suggest that significant quantities of methane can be abated at a net negative cost (ICF International 2015; International Energy Agency 2020). That is, for certain technologies, the cost of investing in abatement to reduce methane emissions is more than offset by the revenues from increased marketable natural gas production. At first glance, this suggests that financial penalties should be effective in achieving methane emissions reductions. The challenge in recent years, however, is that persistent low natural gas prices decrease the returns from an increase in marketable natural gas production and shrink the negative portion of the marginal abatement cost curve.[13] The uncertainties around sources of methane emissions, and the challenges in obtaining accurate measurements, also pose a significant hurdle to regulation through

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Energy Partnership for Environmental Innovation, following an IPCC Tier 3 approach (Environment and Climate Change Canada 2021d).

[13] For example, ICF International (2015) find negative marginal abatement costs for approximately 6,650 kt CO_2e of methane emissions. This result relies on an assumed 2020 natural gas price of $5.00 CAD per thousand cubic feet (Mcf). The actual average 2020 AECO natural gas price (the Western Canadian benchmark) was $2.32 CAD per Mcf. A lower natural gas price decreases the value of conserved gas and moves a share of emissions from the negative to the positive section of the marginal-abatement-cost curve.

financial penalties. As a result, command and control regulation tends to be the primary mechanism to regulate methane emissions.

Command and control regulation for methane emissions from the oil and gas sector can be divided into three general categories: technology-based standards for processes and equipment; performance-based standards for processes and equipment; and leak detection and repair (LDAR) requirements (Munnings and Krupnick 2017). Technology- and performance-based standards typically target methane emissions from venting while LDAR programs target fugitive sources. With technology-based standards, operators are required to use a specific type of equipment or process that minimizes (or eliminates) methane emissions. With performance-based standards, operators have flexibility on the types of equipment or process they use but are required to keep methane emissions (or natural gas releases) below a certain rate or level. Last, LDAR requirements prescribe the activities operators must undertake to monitor their sites for natural gas leaks, as well as repair any leaks they find. In some cases, LDAR requirements may also prescribe a specific leak-detection technology or combination of technologies (e.g. an LDAR "program") for an operator to use.

In 2016, the Government of Canada announced a goal of reducing methane emissions from the oil and gas sector by 40 to 45 per cent below its 2012 baseline by 2025. Federal regulations designed to contribute to this goal consist of six key requirements; four of these came into effect on January 1, 2020 and two will come into effect on January 1, 2023. The regulation outlines an LDAR program that targets fugitive emissions, and a series of performance- and technology-based standards that target general facility venting,[14] venting from compressors and pneumatic devices, venting from well completions involving hydraulic fracturing, and methane emissions from other equipment (Environment and Climate Change Canada 2020e).

The federal regulations are unlikely to apply in the three main oil and gas producing provinces as British Columbia, Alberta and Saskatchewan have all received equivalency agreements for provincial methane regulations (Government of Canada 2020a, 2020b, 2020c). This appears to be largely motivated by each province's desire to implement regulations specific to unique provincial circumstances, and that will be less costly for oil and gas producers than the federal regulations (French 2020). Alberta, for example, estimates that it would cost industry $1.2 billion to meet the federal regulations and $650 million to meet its provincial regulations.

British Columbia and Alberta's regulations are similar to the federal government's in that they largely target specific sources of vented emissions through technology- and performance-based standards, and fugitive emissions through LDAR requirements. Saskatchewan's regulation, in contrast, takes a much more flexible approach. Its primary element requires that large oil licensees meet a single performance-based standard (emissions limit) across all their facilities.[15] Natural gas licensees are not included in the province's emissions management regulation, but are required to implement an LDAR program under an associated directive.

Still uncertain is the effectiveness of the regulations in meeting Canada's methane emissions reduction target. According to the 2021 NIR, Canada's methane emissions from the oil and gas sector were

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[14] General facility venting refers to venting from all sources at a facility apart from the following: (i) Liquids unloading; (ii) A blowdown (temporary depressurization) of equipment or pipelines; (iii) Glycol dehydration; (iv) Use of a pneumatic controller, pneumatic pump or compressor; (v) Start-up or shut-down of equipment; (vi) Well completion; or (vii) Venting in an emergency situation to prevent serious risk to human health or safety (Canada 2020).

[15] Large oil licensees are defined as those with potential emissions of greater than 50,000 tonnes of CO_2e per year across all of their facilities (Saskatchewan 2019).

approximately 44,300 kt CO_2e in 2012, with 42,600 kt CO_2e from the three western provinces.[16] To meet Canada's target, federal and provincial regulations must therefore achieve a minimum emissions reduction of 17,720 kt CO_2e across Canada. According to the estimates completed for the equivalency agreements, however, projected emissions reductions from provincial regulations in British Columbia, Alberta and Saskatchewan only total 13,300 kt CO_2e (Government of Canada 2019, 2020d, 2020e). This implies that even if methane emissions in the remainder of the country are completely eliminated, current regulations will fall well short of meeting Canada's target.

Challenges in methane emissions measurement contribute to further uncertainty regarding the effectiveness of current regulations. In particular, uncertainty around the value of Canada's baseline emissions in 2012 creates corresponding uncertainty about the emissions reductions that are required to meet the target of 40 to 45 per cent below baseline. Johnson et al. (2017), for example, provide top-down emissions estimates and find Alberta will require methane emissions reductions of 924 kt CH_4 (23,100 kt CO_2e) annually to meet the reduction target. In comparison, using the 2012 baseline emissions estimate from the NIR, the target is met with annual methane emissions reductions of only 500 kt CH_4 (12,500 kt CO_2e).

Adding further complication to the potential discrepancy in the methane emissions reduction target is that if the correct target is higher than the baseline, then this in turn implies that emissions reductions must come from sources that have not been formally identified or which are not being accurately measured (Johnson et al. 2017). More robust LDAR requirements that target fugitive emissions, as well as new technologies for identifying fugitive emissions, may help to address these unidentified sources.

Current LDAR requirements at the federal and provincial level, for example, prescribe the use of handheld sensors to identify leaks. Recognizing that monitoring with handheld sensors is a slow and labour-intensive process, current regulation limits the number of required inspections to 1 to 3 times per year (with a minimum separation period of 60 days). This creates the risk of fugitive methane emissions going undetected for extended periods of time. To address these issues, alternative detection technologies — including continuous site monitoring devices and aerial, truck and drone surveys — are being evaluated, and in Alberta, used by some companies as part of an alternative Fugitive Emissions Management Program. The primary objective of these technologies is to achieve equivalent (or improved) mitigation of fugitive methane emissions at lower cost (Kemp and Ravikumar 2021). However, as these technologies are effective at identifying high-emitting sites, with some also being able to quantify emissions at lower costs than traditional sensors, their increased use has the potential to spill over into improved measurement of fugitive emissions (Risk, Atherton, and Gorski 2021).

We also note that it is not only fugitive emissions that contribute to the discrepancies between top-down and bottom-up methane emissions estimates. As identified by Johnson et al. (2017) in Alberta, an additional likely factor is underreporting of volumes of vented emissions. This suggests regulators should introduce stricter reporting requirements that compel facilities to more accurately track and measure known sources of methane emissions. Expanded use of alternative LDAR technologies may also contribute to improved identification of underreporting sites.

Given the uneven distribution of methane emissions amongst oil and gas facilities, there is also an incentive for regulation to support identification of super-emitters, and to impose stricter requirements on these sites (particularly for LDAR programs and reporting requirements). This will ensure that reductions

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[16] The federal government does not appear to have released a baseline level of 2012 methane emissions from the oil and gas sector in any documents related to its target. The estimate we report is the sum of 2012 methane emissions from stationary combustion in the oil and gas sector, from pipeline transportation and from fugitive sources. We do not include any methane emissions associated with non-pipeline transportation in the oil and gas sector as these data are not separated for oil and gas. Notably, this estimate changes slightly from one year to the next as the NIR updates its estimation methodologies.

target the largest sources of emissions. It also reduces the regulatory burden on low-emitting facilities that have potentially already made financial investments in methane emissions reductions through adoption of best practices or emissions-reducing technologies (Atherton et al. 2017).

Last, there is a discrepancy between Canada's methane emissions reduction goal (which is regularly referenced as for the entire oil and gas sector) and its methane reduction regulation (which targets only upstream flaring, venting and fugitive sources from the conventional oil and natural gas sector, in situ oil sands facilities and transmission pipelines). Carbon pricing regulation generally covers methane emissions from incomplete combustion. This leaves, however, methane emissions from refining, natural gas distribution pipelines, oil sands mining and upgrading, and abandoned[17] oil and gas wells as largely unregulated. While an exact measurement of methane emissions attributable to these sources is unavailable, we approximate it at 4,352 kt CO_2e or 9 per cent of the 2012 baseline.[18] Emissions from these sources have increased in recent years, reaching an estimate of 6,238 kt CO2e in 2018.[19] The lack of full coverage, combined with the possibility that methane emissions from uncovered sources may continue to grow, sharply increases the burden on regulated sources to decrease their emissions by well in excess of the stated goal of 40 to 45 per cent.

Agriculture

Sources

In 2019, methane emissions in agriculture were 27,922 kt CO_2e.[20] The large majority of these emissions are methanogenic activity related to livestock production, resulting from enteric fermentation (24,009 kt CO_2e/86 per cent of total agricultural methane) and manure management (3,846 kt CO_2e/14 per cent). Livestock — and, specifically, cattle — is the largest single source of methane emissions in Canada. The remaining methane from agriculture is a result of incomplete combustion from burning agricultural crop residues (37 kt CO_2e/0.1 per cent).[21] As methane emissions from incomplete combustion account for only a minor share of total emissions, we focus on emissions from methanogens in this section.

Enteric fermentation is a digestive process of ruminant animals (herbivorous, hoofed mammals with chambered stomachs) where methanogens residing in the animal's digestive tract convert otherwise indigestible materials like grass and hay into accessible energy. The process results in methane accumulating in the rumen (the first of the stomach chambers) and emitted to the atmosphere through

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[17] As per the NIR, abandoned wells can be further divided into those that are plugged and unplugged, with unplugged wells divided into those without recent production (inactive, temporarily abandoned/suspended or dormant) and those without an operator (orphaned).

[18] Our 2012 estimate of uncovered methane emissions includes the following components: 94 kt CO_2e from oil refining and storage, 824 kt CO_2e from natural gas distribution, 150 kt CO2e from abandoned oil and gas wells and 3,284 kt CO_2e from oil sands mining and upgrading (Johnson and Tyner 2020b; Environment and Climate Change Canada 2021b, 2021c).

[19] Our 2018 estimate of uncovered methane emissions includes the following components: 81 kt CO_2e from oil refining and storage, 984 kt CO_2e from natural gas distribution, 260 kt CO2e from abandoned oil and gas wells and 4,913 kt CO_2e from oil sands mining and upgrading (Johnson and Tyner 2020b; Environment and Climate Change Canada 2021b, 2021c).

[20] This estimate does not include a small amount of methane emissions from incomplete combustion in off-road farm vehicles and stationary farm equipment. Agriculture emissions from these sources are reported grouped together with forestry in the NIR. It is not a significant exclusion, however, as the combined agriculture and forestry estimate of methane emissions from both sources is only 15 kt CO_2e (Environment and Climate Change Canada 2021a).

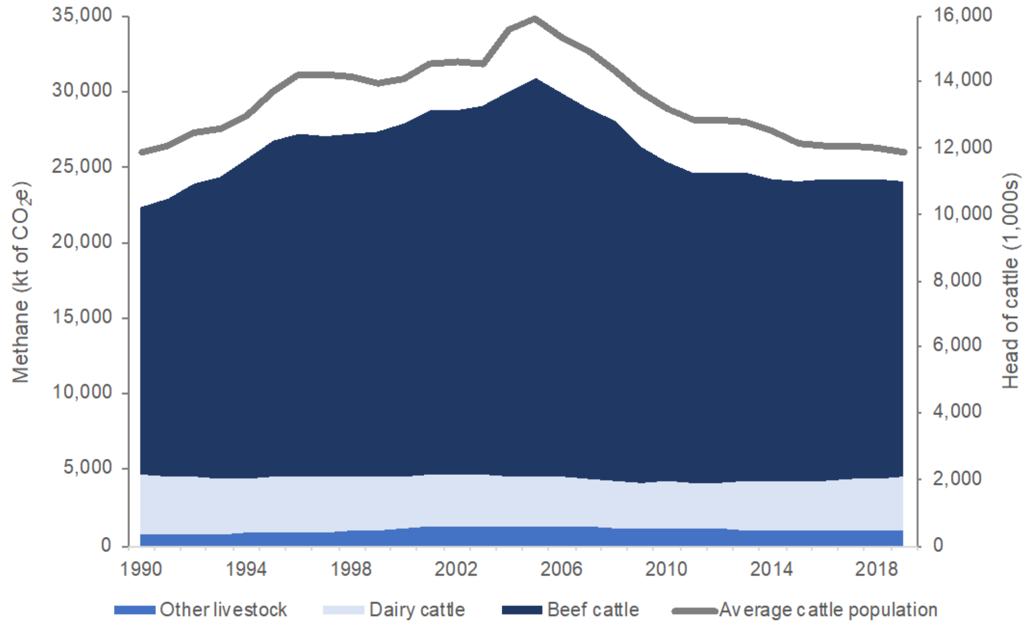
[21] Crop residues may be burned for disposal or to control disease, but the practice is becoming less common in Canada because of negative impacts on soil quality and the environment (Shen et al. 2019).

eructation (belching) and exhalation.[22] The amount of enteric methane produced by an animal is primarily dependent on the type and size of the animal, the amount and composition of its feed, and feed management practices.

The main types of ruminants kept as livestock in Canada are cattle, sheep, goats and bison. Nearly 97 per cent of Canada's enteric methane emissions in 2019 came from cattle (Environment and Climate Change Canada 2021b);[23] cattle are the main ruminant animal kept as livestock in Canada and produce the most methane per head of any ruminant. Enteric methane emission rates differ by type of cattle with dairy cows producing more enteric methane per head than non-dairy cattle.[24] This is because dairy cows require a greater amount of feed to meet the energy requirements of lactation. In general, higher energy requirements translates to more feed consumed by an animal, more enteric fermentation activity and more methane production.

Canada's total methane emissions from enteric fermentation peaked at 30,800 kt CO_2e in 2005 and declined 22 per cent since (Figure 9). This trend follows changes in the size of Canada's cattle population, which also peaked in 2005 and has declined since. As was the case with fugitive emissions in the oil and gas sector, the similarity in trends is in part by construction, as cattle population is a key activity factor in estimating methane emissions from enteric fermentation.

Figure 9: Methane Emissions by Livestock from Enteric Fermentation



Source: Authors' calculations using data from Environment and Climate Change Canada (Environment and Climate Change Canada 2021b).

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[22] Some methane is released later in the digestive process by flatulence. Estimates of the amount emitted through flatulence range from 1 to 5 percent of the total methane emitted by ruminants (Agriculture and Agri-Food Canada 2008; Environment and Climate Change Canada 2021c).

[23] The NIR attributes 1,100 kt CO_2e of methane emissions to other livestock in 2019. Most of these emissions are attributable to swine (527 kt CO_2e), sheep (189 kt CO_2e), buffalo (164 kt CO_2e) and horses (131 kt CO_2e).

[24] Non-dairy cattle include all cattle on beef operations as well as non-lactating cattle on dairy operations (primarily heifers, which are females that have not yet given birth, and calves, which are under one year of age).

The amount of enteric methane emitted per animal has increased over time for both non-dairy cattle and dairy cows. Between 1990 and 2019, the enteric methane emitted per dairy cow increased by 23 per cent. The cause of the emissions increase is major gains in milk production rates, with the amount of milk produced by the average dairy cow increasing by 52 per cent over the same period (Environment and Climate Change Canada 2021c). Increased milk production requires increased feed intake, resulting in more enteric methane emissions. Similarly, the average non-dairy cow today produces 6 per cent more enteric methane than in 1990. This is primarily because the weight of the average beef cow has increased due to market preferences, resulting in more feed required per animal.

The other significant share of Canada's methane from agriculture comes from the collection, storage and use of livestock manure. Manure undergoing anaerobic decomposition by methanogens releases methane. The manure's characteristics (influenced by the type of animal and feed) and manure management practices determine the rate of anaerobic decomposition and therefore methane production. Manure management systems, and practices within systems, vary regionally, by animal type and over time.

Manure storage is a major determinant of methane emissions volumes, as it sets the conditions for manure decomposition. Anaerobic conditions are more likely to occur in intensive agriculture operations where many animals are confined to an area and manure is stored in large piles, for example.[25] Whether the manure is stored dry or wet is also an important factor in emission rates. Liquid manure management systems, where manure is stored wet in tanks or lagoons, generally result in more methane than solid, dry systems. The water mixed in with the manure acts as a barrier to oxygen, increasing anaerobic decomposition.

Among livestock, swine manure is almost exclusively stored wet. Accordingly, it contributes the most methane from manure of any animal group and total methane emissions from manure management track closely with Canada's swine population (Figure 10). For dairy cows and heifers, Canada saw a shift from solid to liquid manure-management systems between 1990 and 2019, contributing to a 200 per cent increase in per-animal manure methane emissions (and a 118 per cent increase in total emissions from the group as a whole). In contrast, manure from non-dairy cattle is typically stored dry. Due to the large population of non-dairy cattle, however, this group is still a marginally larger source of methane emissions from manure management than dairy cows and heifers.

In addition to manure storage, frequency and timing of storage emptying and field spreading affects methane emissions. The sooner manure is moved from storage and spread on crops as fertilizer, where it experiences high oxygen exposure, the shorter the anaerobic decomposition period and the less methane emitted. Climate and weather can also affect methane production, as warmer temperatures and rainfall both increase methanogenic activity.[26]

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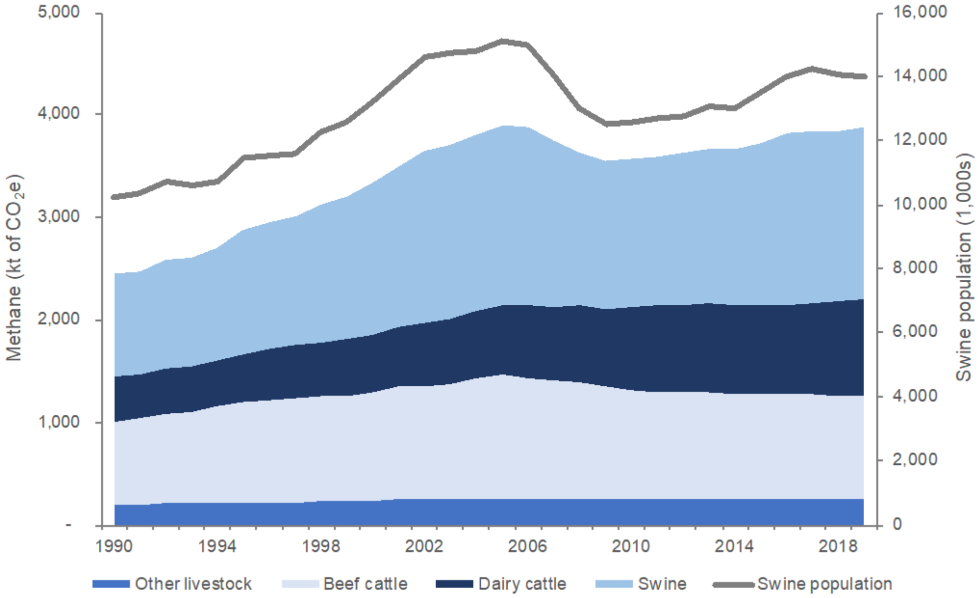
[25] Notably, intensive manure management systems are closest to a point source of emissions of any source of greenhouse gas from agriculture, which are usually diffuse. This creates opportunities for mitigation, discussed later.

[26] Climate is made up of weather events, with weather capturing atmospheric conditions over a short period of time and climate describing what the weather is like over a longer period. Even if climate is overall unchanged, methane releases will be different depending on the weather conditions at the time.

Figure 10: Methane Emissions by Livestock from Manure Management



Source: Authors' calculations using data from Environment and Climate Change Canada (2021a)

Mitigation Options

As almost all of Canada's agricultural methane emissions come from livestock, mitigation efforts are primarily focused on farm-level livestock management practices. The most common and well-researched strategy to reduce methane is to alter an animal's diet to improve feed efficiency. Depending on the animal and the composition of its feed, cattle can lose between 2 and 11 per cent of feed energy as enteric methane (The National Centre for Livestock and the Environment n.d.). This represents a loss of energy that the animal could otherwise use to produce muscle or milk. Improving feed efficiency reduces both methane emissions and producer feed costs. This creates a natural incentive for producers to invest in reducing enteric methane emissions.

Changing the type, quality and composition of feed improves livestock feed efficiency. Increasing fat and grain in rations, for example, are ways to reduce methane from livestock (Agriculture and Agri-Food Canada 2019b, 2020b). Of all feed types, high-grain rations where more than 90 per cent of the animal's dietary dry matter is grain has been shown to make the most meaningful reduction in methane, of 10 to 100 per cent (Agriculture and Agri-Food Canada 2008). Certain grains achieve greater methane reductions; for example, corn is preferred over barley.

There are, however, trade-offs associated with a switch to high-grain feed. First, feeding livestock with grain can counteract the benefit of them converting fibrous material unsuitable for direct human consumption into milk and meat. Grain not otherwise suited to human consumption, such as malting barley, avoids this trade-off. Second, increased grain production requires increased production and transportation of chemical nitrogen fertilizer, an emissions-intensive product. Another trade-off in feed selection is that use of feed types high in dietary protein can cause excretion of higher amounts of excess nitrogen, resulting in higher N_2O emissions (a greenhouse gas that is more potent than methane) from manure (The National Centre for Livestock and the Environment n.d.). Further research to assess the overall greenhouse gas emissions associated with different livestock diets is necessary.

Another mitigation strategy is to add certain substances hindering methane production to animal feed. There are natural compounds, synthetic chemicals, and fats and oils that, when added to livestock feed, inhibit methanogenic activity in the rumen. For example, studying Australian cattle, Kinley et al. (2020) show that beef steers receiving feed made up of 0.10 per cent and 0.20 per cent Asparagopsis (a type of red seaweed) have decreased methane emissions of up to 40 per cent and 98 per cent, respectively. Another option is to add nitrates, which improves rumen fermentation and changes the pathway of hydrogen to produce ammonia rather than methane (Duthie et al. 2018; Troy et al. 2015). Other feed additives proven to result in less enteric methane include ionophores (an antimicrobial agent) and fats or oilseed. Promising additives include plant extracts, biochar and chemical compounds such as the methane-inhibiting chemical compound 3-nitrooxypropanol (3NOP), which Hristov et al. (2015) find reduces methane from dairy cows by 30 per cent. Other feed-related mitigation strategies include feeding cattle forages harvested at optimum maturity, which can maximize digestible energy content and reduce methane emissions by eight per cent, and formulating rations to better match animal nutritional requirements (D. Boadi and Wittenberg 2002).

Where grazing systems feed cattle as opposed to feedlots, producers have fewer options to alter feed. The most readily available option is to improve feed efficiency through pasture management, which involves practices to increase the quality and availability of forage (Agriculture and Agri-Food Canada 2008). A common strategy, for example, is to time grazing to match peak grain quality.

Non-feed-related ways to reduce enteric methane from livestock include genetic selection and potentially vaccination. Certain animals have higher feed-conversion ratios than others, which means they are better at converting feed into functional energy, with less energy lost as enteric methane. Genetic selection to foster this trait can lead to more efficient animals that emit less methane (Basarab et al. 2013). Research is also underway in developing animal vaccines that prevent or reduce enteric methane production. Agriculture and Agri-Food Canada (2019b) estimates ten years before a vaccine may be ready for deployment, however.

Moving up to the farm-level, improving the productivity of individual animals (fewer livestock to achieve the same farm-level output) reduces both enteric methane and methane from manure. Options for achieving lower livestock populations include extending dairy cows' lactation period by switching to more efficient breeds or improving reproductive performance; shortening the time to market for beef cows by increasing rates of weight gain; improving cows' birth rate to require fewer replacement heifers; and culling the breeding herd based on breeding soundness.

In manure management, practices that increase aeration and exposure to oxygen and inhibit methanogenic activity reduce methane emissions. This includes choosing dry systems over liquid systems where possible, storing manure at cooler temperatures, separating solid and liquid manure, and emptying storage systems more frequently. Biological filters can also be used to remove methane from manure, and composting manure can reduce methane emissions (though it may increase N_2O emissions).

A higher-impact approach is use of an anaerobic digester, a facility where micro-organisms decompose manure in the absence of oxygen and that captures the resulting methane. The captured methane becomes fuel, offsetting farm fossil fuel needs. Anaerobic digesters have the potential to significantly reduce methane from manure, but there are barriers to widespread adoption at individual farms (Clark, Wright, and Slomp 2015). First is technical feasibility, including farm infrastructure and design and electricity grid connection. Some farms may lack the infrastructure to accommodate a digester, and the capital investment and technical expertise required to make these changes may act as barriers to uptake. Second is installation costs and electricity and natural gas prices, which influence a farm's cost-benefit decision around deriving its energy and electricity needs from anaerobic digestion.

While not an explicit mitigation strategy, beef demand plays a significant role in determining methane emissions from both enteric fermentation and manure management. Accordingly, dietary shifts, such as growing demand for plant-based meat substitutes, have the potential to contribute to reductions in methane emissions. Heller and Keoleian (2018), studying the production process for the Beyond Meat plant-based burger find that it generates 90 per cent fewer greenhouse gas emissions relative to a conventional beef patty. Also of note, however, is that the per capita availability of beef in Canada — which acts as a proxy for consumption — has been decreasing for the last 45 years, falling by over 50 per cent since its peak in the mid-1970s (Statistics Canada 2021a, 2021c, 2021d). The cattle population, in contrast, has fallen by less than 20 per cent over this same period, with per capita domestic consumption declines offset by growth in both Canada's population and in cattle and beef exports (Statistics Canada 2020e). Recent surveys show that only 25 to 50 per cent of Canadians are open to reducing their beef consumption (Charlebois, Somogyi, and Music 2018; Angus Reid Institute 2019; Agri-Food Analytics Lab 2021), and both Canada's population and global demand for beef are forecast to grow (Statistics Canada 2019; OECD/FAO 2021). Accordingly, it seems unlikely that domestic growth in plant-based meat consumption will translate into significant reductions in methane emissions.

At the policy level, implementation of polluter-pays policies in the agriculture sector — where agricultural producers are taxed or otherwise pay for greenhouse gas emissions resulting from their operations — has been stifled, both globally and in Canada, by concerns about imposing costs on producers and resulting competitiveness and emissions leakage effects (OECD 2019). Many of these concerns reflect the challenges associated with the costs of emissions measurement, reporting, and verification. Specifically, the agriculture sector is comprised of a large number of heterogeneous producers with mostly diffuse sources of emissions. In contrast, costs associated with measurement, reporting and verification of these emissions are fixed and invariant to farm size (Bellassen et al. 2015). Producers therefore face proportionally different cost burdens from participation in mitigation policies, including carbon-pricing schemes. For example, producers operating more intensive, confined livestock operations (i.e. more easily measured and managed point source emissions) will have lower emissions tracking costs in comparison to a smaller-scale grazing operation (i.e. more diffuse emissions, less easy to measure and manage). Using emissions proxies and process-based emissions models instead of direct emissions measurements can help reduce differential costs. Even after accounting for this reduction, however, these approaches are less effective and less cost-effective overall than policies that target emissions directly (OECD 2019).

An alternative to polluter-pay policies is beneficiary-pay policies, where producers are paid for emissions reductions. Examples include government subsidies and offset markets, administered either by the government or as subscription-based private programs where farm-product consumers pay for methane reductions at the farm level. Adoption of expensive technologies such as anaerobic digesters are especially well-suited to support through beneficiary-pays approaches (Kay and Sneeringer 2011).

Similar to the challenges facing polluter-pay policies, beneficiary-pay policies risk introducing distortions into agricultural markets. Offset markets, for example, are criticized for the high cost imposed on producers for registering and marketing emissions reductions, disproportionately affecting smaller producers. It can also be difficult to measure the offsets' additionality, showing that the emissions reduced are a direct result of the offset program and not a reduction that would have otherwise occurred. To mitigate these challenges, hybrid market-based approaches may be favourable. These include tax-and-subsidy policies that recycle emissions tax revenue back to producers to subsidise adoption of low-emission technologies (similar to the model used for large emitters across Canada) or emissions-permit trading schemes.

Governments can also implement policy aimed at creating an enabling market environment. They can help companies overcome barriers to producing methane-reducing feed additives and technologies at scale, for example, through financial support and incentives or fostering cross-sector partnerships. Another tool is introducing standards and labelling schemes to signal low-GHG products (for both agricultural inputs and outputs).

There are currently no regulations in Canada requiring management and reduction of agricultural methane. Consistent with other jurisdictions, federal and provincial carbon pricing programs exclude non-CO_2 emissions from agriculture.[27] As a result, methane emissions from agriculture are the largest source of unregulated and unpriced greenhouse gas emissions in Canada. This lack of regulation is consistent with other countries and reflect the challenges just described. Canada's federal and provincial governments have instead implemented voluntary programs that seek to reward participating farmers for greenhouse gas reductions at the farm level. Such programs include carbon credit schemes, farm-level planning support and funding opportunities.

Alberta and Quebec are currently the only provinces with government-run emissions offset markets. Both markets include protocols that allow participating farmers to earn tradable emissions credits for specific practice improvements resulting in greenhouse gas reductions. Alberta's system currently includes three protocols relevant to methane: feedlot practices, whereby farmers earn credits for emissions reductions achieved through decreasing the amount of time cattle spend in high-density, confined feedlots; genetics, whereby farmers earn credits for emissions reductions achieved through breeding cattle for more efficient feed conversion rates; and biogas, whereby farmers earn credits for generating biogas from agricultural waste (Government of Alberta n.d.). In Quebec's system, the only protocol for agricultural methane is capture and destruction of methane from covered manure storage facilities (Province of Québec 2017).

Both Alberta and Quebec's offset markets stem from early implementation of permit-based provincial carbon pricing programs, which were first put in place in 2007 and 2011 respectively. With similar programs coming into effect across the country, emissions offset markets — and accompanying agricultural methane protocols — are expanding. Both the federal government and the Government of Saskatchewan are in the process of developing offset systems (Saskatchewan Ministry of Environment 2019; Environment and Climate Change Canada 2020b) while New Brunswick is exploring their potential (Government of New Brunswick 2019). Internationally, Australia has arguably the most developed carbon offset market for agriculture. Under Australia's Emissions Reduction Fund, farmers can claim carbon credits for herd management, manure management and for the use of methane-reducing feed additives or supplements (Australian Government 2020).

While not originally developed to target methane emissions, Environmental Farm Programs (EFPs) are another mechanism that can support farm-level emissions reductions. EFPs are voluntary plans that farmers complete to increase their environmental awareness and reduce agricultural operations' impact. EFPs may address energy efficiency, livestock facility management, manure storage and handling, pasture management, soil management, and nutrient management. Although only a small number of provinces have identified EFPs as part of their climate change strategy (Government of Newfoundland and Labrador 2019; Government of New Brunswick 2016), they are available to farmers across the country, generally administered through provincial not-for-profit farm organizations and funded through joint federal-provincial agreements under the Canadian Agricultural Partnership. As a result, they represent a significant opportunity to establish widespread farm-specific plans for methane emissions reductions.

Through the Agricultural Greenhouse Gases Program (AGGP), the Government of Canada also funded research and pilot projects that assess opportunities for farm-level GHG reductions (Agriculture and Agri-Food Canada 2018). The program specifically supported research on methane mitigation, with livestock systems identified as one of its key priority areas. Currently approved projects consider opportunities for

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[27] Concerns around competitiveness impacts has also resulted in the federal carbon pricing system excluding the majority of combustion emissions from on-farm fuel use (primarily when used in farm vehicles and for heating greenhouses).

emissions reductions across all aspects of livestock systems, including feed selection and grazing, and animal and manure management systems.

Waste

Sources

The waste sector accounted for 26,712 kt CO_2e of methane emissions in 2018. The large majority of these emissions are a result of methanogenic activity related to organic solid waste disposal; specifically municipal solid waste (MSW) landfills (22,989 kt CO_2e/86 per cent of total waste methane emissions) and industrial wood waste landfills (3,003 kt CO_2e/11 per cent).[28] The remaining emissions in the sector are a result of wastewater treatment and discharge (532 kt CO_2e/2 per cent), biological treatment of solid waste (187 kt CO_2e/1 per cent), and waste incineration and open burning (1 kt CO_2e/0 per cent). In the first two cases, methane emissions are a result of methanogenic activity, while in the latter case emissions are from incomplete combustion. We focus on waste sector emissions from methanogenic activity in the discussion that follows.

MSW landfills are regulated, publicly run facilities that are the primary destination for most of the waste generated in Canada. This includes residential, industrial, commercial and institutional sources, as well as waste from construction and demolition activity (Environment and Climate Change Canada 2021c). Landfill methane emissions are the result of the anaerobic decomposition of buried organic waste by methanogens. Organic waste is any waste that is composed of natural materials or is derived from a live source. This includes food waste, yard and park waste, paper and cardboard, wood, textiles, disposable diapers, pet waste, sludge, rubber, leather, and construction debris.

Industrial wood-waste landfills are privately owned and operated, by companies in the pulp and paper and solid wood industries. Nearly 100 per cent of the waste in these landfills is organic matter. As a result, despite accounting for a fraction of the total waste sent to landfill, industrial wood-waste landfills account for nearly 12 per cent of total methane emissions attributable to landfills (Environment and Climate Change Canada 2021a).

Waste starts decomposing in a landfill within 10 to 50 days after deposit (Environment and Climate Change Canada 2021c). Decomposition follows an exponential decay function, with annual methane emissions linearly related to the annual amount of decomposed waste. Accordingly, methane emissions are highest in the initial years after waste deposit and decrease exponentially over time. The NIR notes that deposited waste may emit methane for 100 years or more, with most of the emissions occurring in the first 20 years after deposition.

The largest determinants of landfill methane emissions are the quantity of organic waste deposited and the relative composition of the waste. The latter is important as only a portion of any subcategory of organic waste is degradable and further, only a portion of degradable waste will decompose under landfill conditions. The IPCC refers to these characteristics as the share of degradable organic carbon (DOC) and the fraction of degradable organic carbon decomposed (DOC_F).

When multiplied together, the DOC and DOC_F determine the fraction of organic waste that will decompose and generate methane emissions. For example, the IPCC estimates the DOC and DOC_F for

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[28] Up until the 2019 NIR, "Solid waste disposal" was the only waste emissions subcategory for methane emissions attributable to landfilled organic waste decomposition. The data tables accompanying the 2021 National Inventory report (Environment and Climate Change Canada 2021a) include a "Solid Waste Disposal (Landfills)" subcategory. The text of the NIR makes clear that this subcategory only includes emissions from municipal solid waste landfills. Methane emission from wood waste landfills are included in the subcategory of "Industrial Wood Waste Landfills." We refer to MSW landfills in the main text to ensure the distinction is explicit.

food waste are 15 and 70 per cent, respectively. This implies that, on average, for every one tonne of food waste deposited in landfill, 0.105 tonnes (10.5 per cent) will generate methane emissions. The IPCC estimates of DOC values for specific categories of organic waste range from a low of 15 per cent for food waste to a high of 43 per cent for wood (IPCC 2006).[29] The DOC_F ranges from a low of 10 per cent for less decomposable waste to a high of 70 per cent for highly decomposable waste (IPCC 2019a).[30]

Another important determinant of methane emissions from landfills is decomposing waste's rate of exponential decay.[31] A higher rate of exponential decay means that waste will decompose faster, which in turn means that it will emit higher amounts of methane in the years after initial deposit. This is again influenced by the type of landfilled waste, with highly decomposable waste (that is, organic waste with a higher DOC_F) tending to break down at a faster rate. As waste decomposition is a microbial reaction, the environmental conditions of the landfill will also influence methane emissions.

Last, oxidization of methanogens by the landfill cover affects the amount of methane released to the atmosphere. Landfill regulations typically require that landfill sites put down a daily cover of soil or other material. Additionally, a final cover is required when a landfill is at capacity and will no longer be used. Oxidization occurs when the methanogens generated by organic decomposition pass through the cover and react with methane-consuming bacteria (known as methanatrophs). The reaction converts the methane to carbon dioxide, which, although still a greenhouse gas, is preferable to methane due to its smaller global warming potential.

A unique attribute of methane emissions from landfills is that only accumulated waste matters in determining current-year emissions. As a result, while current decisions about waste diversion and treatment are still important, these decisions will primarily reduce future methane emissions. Methane generation from previously landfilled organic waste's decomposition is unavoidable and mitigation is generally only possible through landfill cover or methane capture technologies. This is most evident when considering the trends in landfill methane emissions over time. For example, despite annual waste deposits to MSW landfills fluctuating from one year to the next, the amount of methane generated follows a relative smooth path (Figure 11). A steady drop in emitted methane between 2004 and 2012 is only due to substantial increases in volumes of methane captured and flared (+2,900 kt CO_2e) and captured and used for energy (+1,000 kt CO_2e) at landfill sites.

The effect of accumulated waste on annual methane emissions is even more pronounced in wood waste landfills, where annual deposited waste decreased by 98 per cent between 1990 and 2019 (Figure 12). In comparison, annual methane emissions declined by only 22 per cent over the same period. Further, annual methane emissions did not start decreasing until 2001, by which point estimates of deposits to wood waste landfills had already fallen by 55 per cent relative to their peak in 1990.

Methane emissions from wastewater treatment and discharge and biological treatment of solid waste are also attributable to methanogens decomposing organic waste in an anaerobic environment. Both sources, however, contribute only minor amounts of methane emissions.

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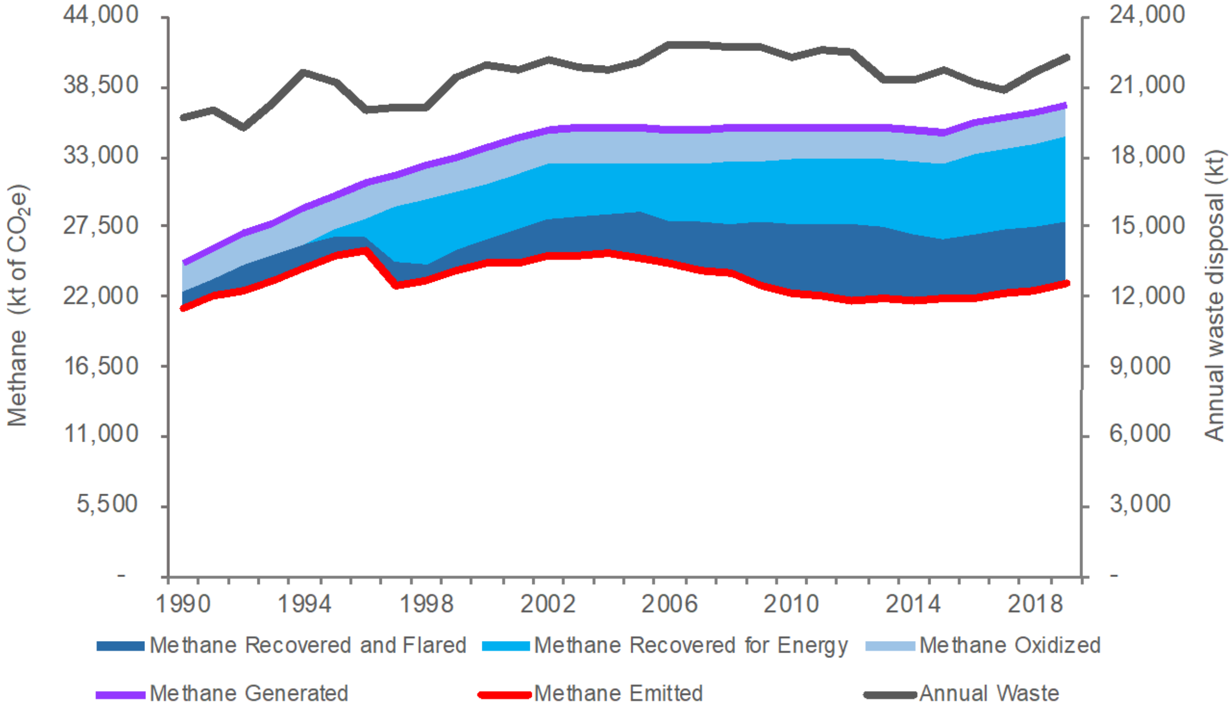
[29] The remaining DOC values are: 20 per cent for garden and park waste, 22 per cent for construction debris, 24 per cent for textiles, 24 per cent for diapers and pet waste, 30 per cent for sewage sludge, 39 per cent for rubber and leather, and 40 per cent for paper and cardboard.

[30] Examples of highly decomposable waste are food waste and grass; examples of moderately decomposable waste are paper products including coated paper, old newsprint, old corrugated containers and office paper; and examples of less decomposable waste are tree branches and harvested wood products (IPCC 2019a). Notably, however, there can also be significant variation within these categories. For example, the IPCC guidelines also note that the DOC_F for paper products ranges from 21 to 96 per cent; paper derived from mechanical pulp is less degradable than paper derived from chemical pulp.

[31] The IPCC and the NIR refer to the rate of exponential decay as the "reaction constant."

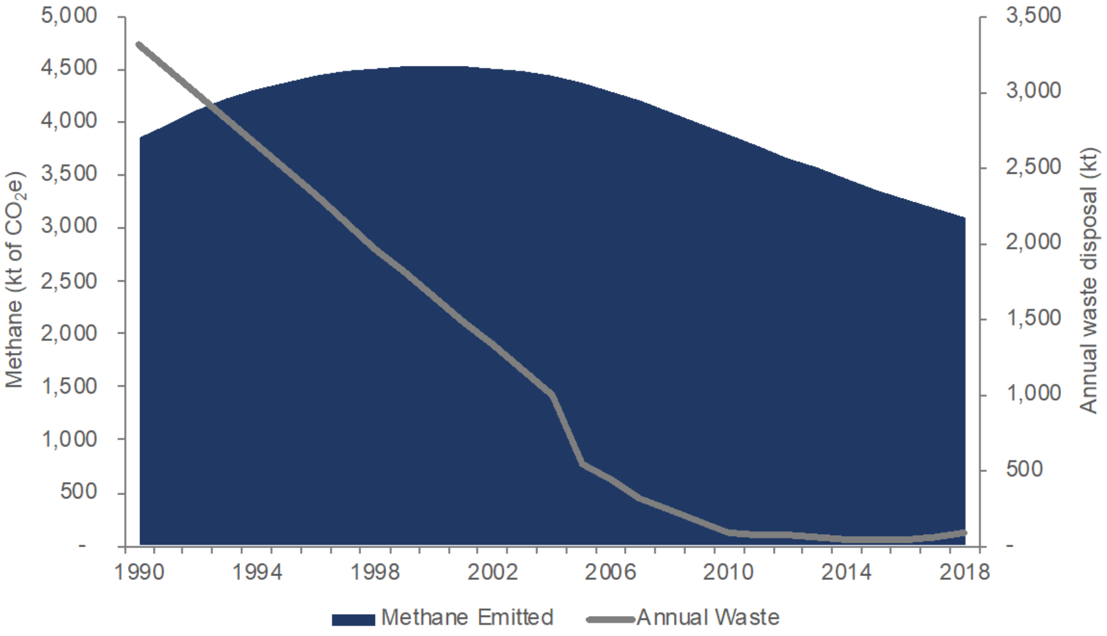
Figure 11: Methane Generated from Municipal Solid Waste (MSW) Landfills



Source: Authors' calculations using data from Environment and Climate Change Canada (2021b).

Note: "Methane Emitted" is equal to "Methane Generated" minus the amounts of generated methane that are oxidized, recovered and flared, and recovered for energy (used as biogas for heat or electricity generation).

Figure 12: Wood Waste Landfill Methane Emissions



Source: Authors' calculations using data from Environment and Climate Change Canada (2021b).

Note: The NIR assumes that none of the methane generated at wood waste landfills is captured and combusted. Rather, all generated methane emits to the atmosphere.

For wastewater treatment and discharge, it is more common in Canada for organic waste to be treated or to decompose in an aerobic treatment system, where the availability of oxygen suppresses methanogenic activity. Specifically, in 2018, only 21 per cent of Canada's population discharged their wastewater to an anaerobic treatment system that generates methane emissions. The most common is a septic system (serving 15.7 per cent of Canada's population), where approximately half of the organic load in wastewater settles in a septic tank and decomposes under anaerobic conditions (Scheehle and Doorn 2001).[32]

Methane emissions from wastewater are a function of the water's organic load. The key measure is the per-capita organics loading rate,[33] which approximates each individual's daily contribution to the organic load in wastewater. As this measure increases, the amount of organics subject to decomposition, and accordingly methane emissions, also increases.

The biological treatment of solid waste category accounts for methane emissions from both composting and anerobic digestion. Composting organic waste means it decomposes in an aerobic environment and does not generate any methane emissions. In practice, however, it is nearly impossible for a composting site to maintain aerobic conditions for all deposited waste at all times. As a result, while composting leads to a drastic reduction in methane emissions relative to landfills, all compost sites will generally have some small level of methane emissions.[34] The key determinant of methane emissions from composting is how well a compost site is able to maintain aerobic conditions. Beyond this, they are subject to the same determinants as methane emissions from a solid waste landfill. Key among these is the oxidization rate as compost has a high share of methanotrophic bacteria, which will oxidize a significant share of the methanogens formed in anaerobic pockets of the compost site (Lou and Nair 2009).

Anaerobic digesters are an alternative option for the treatment of organic waste. Similar to the agriculture sector, organic waste that is sent to an anaerobic digester is broken down by micro-organisms in an environment without oxygen. The resulting methane emissions are captured and upgraded and the biogas is used as fuel. Direct methane emissions from anaerobic digesters are therefore limited to the amount of gas that is lost through on-site leakage.

Mitigation Options

Mitigation options for methane emissions from the waste sector generally fit in two categories: upstream diversion and downstream recovery.[35] With upstream diversion, organic waste is rerouted from a waste management stream where it will undergo anaerobic decomposition. With downstream recovery, the anaerobic decomposition of organic waste continues to generate methane emissions but landfill

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[32] The remaining half of the organic load in septic systems flows through to a drainage field and decomposes under aerobic conditions.

[33] Measurement is BOD_5/person/day, where BOD_5 is an indicator called five-day biological oxygen demand. This measures the amount of oxygen consumed by microorganisms over a 5-day period while breaking down organic matter found in wastewater.

[34] We estimate that relative to sending organic waste to landfill, composting reduces total lifetime decomposition emissions by 96 to 99 per cent. We derive this estimate by following the NIR's estimation methodology for methane missions from landfilled waste and methane emissions from composting.

[35] In this section, we focus on mitigation options for methane emissions from solid-waste landfills. This is largely because mitigation options for methane emissions from biological treatment of solid waste and from wastewater treatment are limited. Biological treatment of solid waste is itself a mitigation option relative to sending waste to landfill. Further reducing emissions therefore requires reducing waste generation. The main option for mitigating methane emissions from wastewater treatment is to transition treatment technologies from anaerobic to aerobic systems. However, the largest source of anaerobic wastewater emissions in Canada is septic systems, for which aerobic replacement options are limited.

management strategies lead to the reduction or capture of these emissions before they are released to the atmosphere.

Diversion options exist at the waste management level and at the residential- and business-level. The primary option at the management level is to send waste to an incinerator or energy-from-waste facility. Facility capacity limits this, however. Canada had 46 publicly owned thermal waste facilities in 2018 (Statistics Canada 2021b). ECCC classifies only six of these facilities as large, however, and only a small share (approximately 5 per cent in 2018) of waste is incinerated each year (Environment and Climate Change Canada 2019, 2021c). Additionally, since 2010, five major waste-to-energy projects were cancelled. This is largely attributable to two factors. First, the high cost of incineration and second, the uncertainty that current waste-reduction efforts create around the volume of future waste streams; in particular, whether they will be high enough to support a thermal treatment facility (Chung 2018). Of additional concern is whether new thermal waste facilities may negate waste diversion efforts. Baxter et al. (2016), for example, find that individuals are less likely to divert waste (compost or recycle) if they know waste is being sent to a thermal treatment facility.

Limitations to waste diversion at the waste management level create a strong argument for focusing diversion efforts at households and businesses. The two most common options are recycling and composting. Recycling, which is primarily an option for paper and wood waste, diverts organic waste from the waste stream. Accordingly, it completely mitigates methane emissions. Composting, in comparison, is primarily a diversion option for food and yard (garden) waste, soiled paper products and pet waste. Some municipalities also accept diapers and smaller types of wood waste (e.g., popsicle sticks or wood shavings) in their composting programs.

Initiatives that aim at reducing waste or reusing items that may otherwise enter the waste stream also fall in the diversion category. Unlike recycling and composting, which are generally only applicable to specific subcategories of organic waste, reduce and reuse options exist across all organic waste categories. Notably, however, while government can directly support — and even legislate — use of recycling and compost, opportunities for direct government involvement in reuse and reduce initiatives are more limited. The most common avenues of government involvement tend to be indirect and can include education campaigns, funding opportunities and research.

Substantive increases in composting and recycling over the last 30 years, largely motivated by the introduction of municipal collection programs, has helped to limit the growth in landfilled waste. Despite this shift, however, organic waste continues to make up the majority of landfilled waste in Canada each year.[36] Also of note is the previously referenced lag between increases in waste diversion and decreases in landfill methane emissions. When considered together, these two factors point towards the necessity of also adopting downstream recovery policies to achieve significant reductions in methane emissions from waste.

There are two primary options for reducing methane generated from landfills. The first is landfill gas recovery, where wells are drilled into the landfill to retrieve methane. The retrieved methane is pumped to the surface, processed and is flared, used for generating heat or electricity, or sold as renewable natural gas (U.S. Environmental Protection Agency n.d.-b). In 2019, the NIR estimates that landfill-gas recovery

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[36] Estimates from 2016 indicate that Canada sent 20.3 million tonnes of waste to landfill, with organic waste accounting for 63 per cent of this total (Environment and Climate Change Canada 2020d). The two largest sources of landfilled organic waste are paper (2.5 million tonnes) and food (5.8 million tonnes), two categories for which diversion alternatives are readily available. Further, the national paper diversion rate was only 57 per cent in 2016 while the diversion rate for food and yard waste (reported together as these are the most commonly composted streams) was only 27 per cent.

systems captured just over 462 tonnes of methane (corresponding to 11,553 tonnes CO_2e or 31 per cent of total methane emissions generated by landfills).

The second option for reducing methane from landfills is through the landfill cover. As previously discussed, the landfill cover oxidizes generated methanogens and reduces the amount of atmospheric methane release. The NIR's estimation methodology assumes an oxidization rate of 10 per cent, which corresponds to just over 2,500 kt CO_2e of methane mitigated in 2019. There is evidence to suggest, however, that this rate is likely an underestimate (Chanton, Powelson, and Green 2009). It also reflects the estimated oxidization rate for a conventional landfill cover chosen to target a range of externalities such as odor, wind-blown refuse, and attraction of vermin and other wildlife.

Choosing a cover to minimize methane emissions means the oxidization rate can increase substantially. For example, organic material has a greater share of methanatrophic bacteria and will therefore have higher oxidization rates than a conventional material such as soil (Conestoga-Rovers & Associates 2011). In an application in British Columbia, fertilizer derived from wastewater biosolids was combined with woodchips and sawdust and applied as a final cover to several regional landfills. The reduction in methane emissions attributable to this cover is estimated at 90 per cent (MetroVancouver n.d.). Final covers can also minimize methane emissions generation. For example, an evapotranspiration cover retains precipitation by design. Accordingly, it minimizes the amount of moisture that reaches the landfilled waste and results in a drier environment that is less favourable to methanogenic activity.

The Government of Canada does not currently have any explicit regulations that target reducing methane emissions from landfills, though it has committed to developing these regulations (Environment and Climate Change Canada 2020a). Further, landfill emissions are also excluded from the federal government's carbon price. As a result, regulation of landfill emissions is currently limited to a small number of provincial initiatives, with landfills in most provinces not facing any explicit regulation. The lack of federal government involvement in regulation of methane emissions from landfills is likely attributable to waste sector regulation falling primarily under provincial jurisdiction, while the day-to-day management of the waste system is primarily a municipal responsibility. The federal government's main contribution to methane reduction in the waste sector is through various funding programs that support research and development, educational programs and retrofits to current waste management sites. With food waste continuing to be the largest category of all residual waste landfilled in Canada, the federal government has also identified achieving reductions in food waste as an emerging area of focus (Agriculture and Agri-Food Canada 2019a). Again, however, the primary action it has announced in support of this objective is a new funding program (Agriculture and Agri-Food Canada 2020a).

Provinces and municipalities have more tangible actions to reduce landfill methane emissions. Both British Columbia and Ontario have regulations requiring landfills over a certain size to capture and combust methane. Manitoba previously had similar requirements under its *Climate Change and Emissions Reduction Act*. While the Act was repealed in 2018, systems installed under the Act are still operating. There is no explicit regulatory requirement for landfill gas capture in the remaining provinces and territories.[37] Carbon offset markets in Alberta and Quebec, however, both include protocols for landfill gas capture and combustion.

The absence of wider-spread regulations requiring landfill gas combustion represents a significant gap in Canada's overall climate policy. In the U.S., for example, regulations under the Clean Air Act require all

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[37] Although Alberta does not have an explicit requirement to capture and combust methane, it is the only province where landfills face an emissions price. Specifically, under Alberta's Technology Innovation and Emissions Reduction Regulation any landfill with CO_2e emissions in excess of 100,000 tonnes per year must meet either a target for emissions reductions or pay a carbon price on emissions that exceed this target. Our review of Environment and Climate Change Canada's large emitters database suggests there is currently only one landfill in Alberta that meets this criteria (Environment and Climate Change Canada 2020c).

landfills above a certain size to install and operate a system to collect and control landfill gas. The U.S. Environmental Protection Agency (EPA) additionally runs a Landfill Methane Outreach Program (LMOP) which ". . . works cooperatively with industry stakeholders and waste officials to reduce or avoid methane emissions from landfills" (U.S. Environmental Protection Agency n.d.-a). As of August 2020, 726 of 1,289 open landfills in the LMOP's project database had either a flare installed or an operating project for landfill gas recovery and use (U.S. Environmental Protection Agency 2020). In comparison, Canada has only 99 landfill gas capture systems in place (Canadian Biogas Association 2021). Also of note is that due to safety concerns, most provinces have regulatory requirements for landfill gas monitoring and capture (should gas levels exceed a certain limit). In the absence of accompanying regulation requiring landfill-gas combustion, direct venting of the gas to the atmosphere is considered an acceptable method of disposal.

Landfill diversion bans are another example of concrete actions by provincial and municipal governments to reduce methane emissions from landfills. Nova Scotia was an early mover in this regard, introducing landfill bans on corrugated cardboard, newsprint, and leaf and yard waste in 1996, and extending it to include all compostable organic material in 1997 (Nova Scotia 2019). Prince Edward Island currently has the most comprehensive program, which requires mandatory sorting of all waste in the province. Improperly sorted residential waste will not be collected while commercial waste may either be rejected or subject to a disposal surcharge.

There are no other current province-wide bans on organic waste, although Ontario is considering the introduction of one in 2022, and numerous other provinces have either organic-waste diversion targets or offer funding to support municipal diversion initiatives. Alberta has also established offset credit protocols for aerobic composting projects and for energy generation from biomass-waste combustion. In British Columbia, municipal organic waste bans are currently in place in Metro Vancouver, the Capital Regional District (Victoria) and Nanaimo. These bans cover 64 per cent of British Columbia's population (Government of British Columbia n.d.). Another common municipal diversion strategy is disposal surcharges on waste delivered direct to landfill and exceeding a fixed percentage of recyclables or organic materials. At the household level, municipalities may place strict limits on the amount of curbside waste collection, while allowing more flexibility in volumes of recycling and compost.

Last, product stewardship and extended producer responsibility (EPR) programs, most commonly adopted at the provincial level, are an increasingly common approach for supporting waste diversion from landfills. Under these programs, suppliers assume some level of responsibility for the post-consumer phase — effectively the disposal — of materials they sell. Programs typically take the form of suppliers providing funding to support municipally-run recycling programs (product stewardship), a supplier organization assuming full financial and physical responsibility for product disposal (full EPR) or some combination of the two (shared EPR) (Arnold 2019). While these programs extend to a range of waste categories, the most notable from the perspective of reducing methane emissions are those for packaging and paper products (PPP). British Columbia, Saskatchewan, Manitoba, Ontario and Quebec currently have either a product stewardship or an EPR program for PPP in place. A number of these provinces are in the process of strengthening their programs (transitioning from product stewardship to full EPR) while most of the remaining provinces and territories are actively considering or are in the process of developing programs.

Conclusion

In this paper, we provide a detailed review of Canada's methane emissions, discussing the contribution of the three sectors responsible for almost 100 per cent of Canada's anthropogenic emissions — oil and gas, agriculture and waste — and mitigation opportunities for each. Our review reveals that emissions measurement challenges hinder methane management across all sources. Methane releases from many diffuse sources, natural and anthropogenic, which makes it difficult to track and quantify, as well as to identify all individual sources and attribute emissions to any one specific point source. For this reason, there is high uncertainty surrounding current estimates.

The high uncertainty in estimates of the level of methane emissions leads to uncertainty in the contribution of methane to Canada's overall greenhouse gas emissions profile. Further exacerbating these uncertainties are the different values for methane's GWP. Of particular note is that the IPCC's current recommendation is for countries to translate methane estimates into carbon-dioxide equivalent units using a 100-year GWP of 25, while the most recent knowledge suggests the 100-year GWP falls in the range of 28 to 36. This indicates that Canada's baseline methane emissions estimate — before accounting for any errors due to measurement challenges — is an underestimate by 20 to 30 per cent. This in turn means that any emissions reduction goals, such as the government's target for the oil and gas sector, will require more aggressive policy.

Measurement challenges also affect policy options to mitigate emissions. Financial penalties such as an emissions price, for example, are less viable due to their reliance on accurate measurement and attribution. Similarly, difficulty determining accurate emissions baselines is a barrier to effective performance-based regulation. Concerns of imposing high measurement costs on producers further hinders policy action.

As a powerful climate-forcing greenhouse gas with measurement and management challenges, methane demands greater attention and action. Political interest thus far has been narrow in scope, focused primarily on managing methane from the oil and gas sector. With federal and provincial regulatory frameworks now in place for the management of most sources of oil and gas methane, we can expect to see tangible methane reductions and lessons in efficient methane regulation. This creates the need — and opportunity — for further research on regulatory outcomes and how these relate to regulatory design across jurisdictions. In the near-term, further research is required to verify baseline methane emissions estimates for the oil and gas sector, to independently track emissions reductions, and to identify unreported emissions sources or reporting errors that may impede progress towards Canada's target of achieving a 45 per cent reduction in oil and gas methane against 2012 levels by 2025. Also important is recognition that coverage is incomplete for some oil and gas methane sources (the downstream sector, oil sands mining and upgrading, and abandoned oil and gas wells), and additional policy levers are necessary to address these gaps.

In contrast to the oil and gas sector, there is little political or policy action to address methane emissions from agriculture and waste. As a result, methane emissions from agriculture is the largest source of unregulated and unpriced greenhouse gas emissions in Canada. Opportunities exist for creative, hybrid market-based approaches to stimulate farm-level emissions reductions while limiting market distortions. These opportunities will not be realized, however, without further research and policy development. In the waste sector, the absence of regulations requiring landfill gas combustion represents a significant gap in Canada's overall climate policy. Jurisdictional challenges appear to be hindering landfill-specific mitigation at scale. The federal promise to develop landfill emissions regulations is a step in the right direction. Opportunities also exist for further emissions reductions through household- and business-level waste diversion, particularly through extended producer responsibility models. As there is a limited body of knowledge on policy options for managing methane from agriculture and waste, further research in both sectors is essential.

Despite the significant contribution of methane to Canada's greenhouse gas emissions profile, it continues to receive insufficient attention in climate change discussions. Across all methane emissions sources there is an on-going need for further research on cost-effective regulation, especially the design of rules that incentivize development and adoption of best practices and emissions-reduction technology. Federal and provincial governments should also address improving and standardizing current methane emission estimates, formally identify unregulated emissions sources, and explore either stricter regulations or well-defined market-based approaches with measurable outcomes. Looking ahead, Canada’s long-term climate goals are ambitious. Taking steps to ascertain the true level of Canada's methane emissions and to develop a comprehensive and concrete plan that addresses methane from all sources is an important part of securing a smooth path towards these goals.

Appendix A: Methane Emissions Estimates, 2019

Table 1: 2019 Methane and Greenhouse Gas Emissions Estimates by IPCC Reporting Category

Emissions Categories	2019 Methane Emissions (kt of CO_2e)	2019 Total GHG Emissions (kt of CO_2e)	Methane as Share of Category Emissions	Methane as Share of Total Methane Emissions	Methane as Share of Total GHG Emissions
Energy	**42,990**	**589,288**	**7.3%**	**44.0%**	**5.9%**
Stationary Combustion	4,225	318,670	1.3%	4.3%	0.6%
Transport	978	216,770	0.5%	1.0%	0.1%
Fugitive Sources	37,787	53,846	70.2%	38.7%	5.2%
Industrial Processes and Product Use (IPPU)	**137**	**54,318**	**0.3%**	**0.1%**	**0.0%**
Mineral Products	-	8,831	-	-	-
Chemical Industry	135	6,814	2.0%	0.1%	0.0%
Metal Production	2	13,846	0.0%	0.0%	0.0%
Production and Consumption of Halocarbons	-	12,445	-	-	-
Non-Energy Products from Fuels and Solvent Use	-	11,633	-	-	-
Other Product Manufacture and Use	-	750	-	-	-
Agriculture	**27,922**	**59,058**	**47.3%**	**28.6%**	**3.8%**
Enteric Fermentation	24,009	24,009	100.0%	24.6%	3.3%
Manure Management	3,876	7,924	48,9%	4.0%	0.5%
Agriculture Soils	-	24,445	-	-	-
Field Burning of Agricultural Residues	37	49	76.4%	0.0%	0.0%
Liming, Urea Application and Other Carbon containing Fertilizer	-	2,631	-	-	-
Waste	**26,712**	**27,581**	**96.8%**	**27.3%**	**3.7%**
Solid Waste Disposal	22,989	22,989	100.0%	23.5%	3.1%
Biological Treatment of Solid Waste	187	381	49.1%	0.2%	0.0%
Wastewater Treatment and Discharge	532	1,021	52.0%	0.5%	0.1%
Incineration and Open Burning of Waste	1	187	0.7%	0.0%	0.0%
Industrial Wood-Waste Landfills	3,003	3,003	100.0%	3.1%	0.4%
Total Canada	**97,761**	**730,245**	**13.4%**	**100.0%**	**13.4%**
Land Use, Land Use Change and Forestry	**623**	**9,878**	**N/A**	**N/A**	**N/A**
Forest Land	375	-133,274			
Cropland	114	-4,220			
Grassland	1	1			
Wetlands	15	2,614			
Settlements	118	2,173			
Harvested wood products	-	142,584			

Source: Environment and Climate Change Canada (2021a)

Appendix B: NIR Estimation Methodology by Sector

Oil and Gas Sector (Fugitive Sources)

The large size of Canada's oil and gas sector, which includes hundreds of thousands of oil and gas wells and hundreds of thousands of kilometers of pipelines (along with associated equipment, storage facilities, processing plants and refineries), creates significant challenges for methane measurement. Constrained by this, Canada's NIR largely relies on an assumption of average emissions rates by facility type to calculate the official estimates of methane emissions from oil and gas.

For each fugitive reporting category required by the UNFCCC, the NIR specifies the emissions sources that contribute to that category.[38] For most sources, base-year emissions estimates are derived from detailed consultant reports for different oil and gas subsectors.[39] Current-year emissions are then extrapolated by multiplying the base year emissions estimate by the ratio of an activity factor for the current year to the same activity factor in the base year.[40] Notably, the implicit assumption in this approach is that forecast methane emissions change linearly with the activity factor. That is, if the activity factor is 50 per cent higher than the base year then the extrapolated methane emissions estimate will similarly be 50 per cent higher than the base year.

Fugitive methane emissions from flaring are the most straight-forward to estimate as the only emissions source is flaring itself and the activity factor is most often reported flaring volumes. Of note is that starting in 2010, methane emissions from flaring in Alberta are directly estimated using the conventional bottom-up approach of multiplying an emission factor by an activity factor. The activity factor is reported flaring volumes while the emission factors are specific to Alberta townships. The variance in emission factors by township reflects regional differences in gas composition throughout Alberta. While methane emissions estimated using this approach will still change linearly with the activity factor, the use of township-specific data provides additional accuracy not captured by the consultant reports.

For vented methane emissions, the NIR identifies three separate emissions sources — reported venting, unreported venting and glycol dehydrator off-gas. As its name suggests, the activity factor for reported venting is most often venting volumes reported by oil and gas operators. Similar to flaring emissions, starting in 2010, reported venting emissions in Alberta are directly estimated by multiplying the volume of gas vented in a township by the township-specific mole fraction of methane[41] and the density of methane at standard conditions.

Methane emissions from unreported venting and glycol dehydrators in all years are estimated using the base year estimates from the consulting reports as the emissions factor. Unreported venting mainly captures controlled venting emissions from natural gas driven equipment — for example, pneumatic

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[38] This information is found in Annex 3, Table A3.2-5 of Part 2 of the 2021 National Inventory Report (Environment and Climate Change Canada 2021d).

[39] The five subsectors for which detailed consultant reports are available are: (1) Upstream oil and natural gas production (including in-situ bitumen extraction); (2) Natural gas transmission and storage; (3) Petroleum refining; (4) Natural gas distribution; and (5) Oil sands (mining) and heavy oil upgrading. The only subsector for which no Canadian data is available is abandoned oil and gas wells. As a result, the NIR's estimate of Canadian emissions relies on data from a study on fugitive emissions from abandoned oil and gas wells in the United States.

[40] Exceptions to this approach are the following: Flaring and reported venting emissions from the upstream oil and gas sector in Alberta for the period of 2010 to 2019, unintentional fugitive emissions from the petroleum-refining sector, and unintentional fugitive emissions from abandoned oil and gas wells. In each of these cases, emissions are estimated by the more conventional bottom-up approach of multiplying an activity factor by an emissions factor.

[41] The mole fraction of methane is the fraction of molecules in natural gas that are methane.

devices and compressors — for which there is no reporting requirement.[42] Venting of glycol dehydrator off-gas is similarly a controlled process for which emissions are not reported. As a result, for both these categories emissions estimation relies on activity factors that are effectively production- and infrastructure-related count data, and which offer no direct measurement of venting volumes.[43] These activity factors include oil and gas production (including crude bitumen and synthetic crude oil), number of wells drilled, volumes of natural gas delivered to and received from storage and kilometers of pipeline.

These same activity factors, as well as provincial oil and gas well inventories and the annual number of spills and pipeline ruptures, are used along with base-year emissions factors derived from the consulting reports to generate the estimates of methane emissions from the large majority of oil and natural gas fugitive emissions sources. The implication of this approach is that the extrapolated value of the NIR's fugitive methane emissions estimate is almost exclusively dependent on activity factors that offer no measurement of natural gas or direct methane releases. Rather, it relies heavily on the assumption of a static and homogenous relationship between fugitive emissions and oil and gas sector activity and infrastructure.

A comparison of national methane emissions estimates for Canada's oil and gas sector from a collection of studies can be found in the International Energy Agency's methane tracker database (International Energy Agency 2021). A full discussion of the individual studies and their methodologies is beyond the scope of this paper. However, it is interesting to note that of the eight estimates reported, Canada's official estimate from the NIR is the smallest (by factors ranging from approximately 25 to 100 per cent).[44] This result further underscores the challenges in measuring methane emissions from the oil and gas sector. It also emphasizes the need to view and interpret current estimates with a degree of caution as significant uncertainty remains around the true magnitude of emissions.

Agriculture

Canada estimates agricultural methane emissions using a conventional bottom-up approach applied at the provincial level and then aggregated to obtain national estimates. For both enteric fermentation and manure management, the emission- and activity-factors are specific to animal type or in the case of cattle, animal subtype and production stage. The activity factor is livestock population while the emission factor captures a variety of influencing factors on an animal's methane emissions. These include an animal's average size and productivity, its gross energy intake, type of feed, herd characteristics and farm management practices.[45] The impact of these diverse factors means the emission factors for livestock methane emissions can change annually, making it challenging to obtain accurate estimates.

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[42] The NIR defines unreported venting as: ". . . venting from processes or equipment that is not typically included in reported venting volumes. This includes pneumatic devices (e.g., chemical injection pumps, natural gas operated instrumentation), compressor start gas, purge gas and blanket gas that is discharged directly to the atmosphere and gas vented from drill-stem tests" (Environment and Climate Change Canada 2021d).

[43] A national breakdown of the NIR venting methane emissions estimate between reported and unreported sources is not available. However, Johnson et al (2017), which looks at the NIR methane estimates for Alberta in 2014, indicates that methane emissions from reported venting account for approximately 44 per cent of total venting methane emissions. As Alberta accounts for nearly 60 per cent of national venting methane emissions, it is reasonable to expect that unreported sources also comprise the majority of the national venting emissions estimate.

[44] Two of the eight estimates that are reported are from the IEA and Canada's NIR. The remaining six estimates are from the following sources: U.S. Environmental Protection Agency (2012), ICF International (2015), Höglund-Isaksson (2017), Hoesley et al. (2018), Crippa et al. (2019) and Maasakkers et al. (2019).

[45] Herd characteristics refers to the proportion of animals in different production stages. For example,e beef cows or replacement heifers, which live for longer and therefore produce more methane, or finishing animals such as slaughter heifers and steers, which have shorter lifespans and therefore a lower emission factor. Farm management

The emission factors for enteric methane from cattle are a function of three key variables: an animal's gross daily energy intake in a specific production stage, the rate at which gross energy is converted to methane in that same production stage and the numbers of days per year that an animal spends in that stage. The NIR uses the IPCC default parameter for the methane conversion rates for non-dairy cattle, whereas for dairy cattle the methane conversion rate is based on production data and methane prediction equations from North American research. The gross energy intake and number of days spent in a production stage are calculated as a function of both Canada-specific data and IPCC default parameters. The Canada-specific data includes location (province), climate, the type of cattle (dairy or non-dairy), and typical characteristics of the animal (physiological status, diet, age, sex, weight, growth rate, activity level and production environment).[46] These data are primarily from a study by Boadi et al. (2004), with adjustments made to account for changes in trends since the early 2000s. For example, Canada recently adjusted the dairy cattle model to better account for both regional differences in practices and the significant increase in milk productivity achieved in the past 15 years.

The reliance on IPCC default parameters introduces significant uncertainty to Canada's estimates of enteric fermentation emission factors. For example, the use of the IPCC default parameter for the methane conversion rate for non-dairy cattle contributes to a high range of uncertainty (41%) in the enteric methane emission factor for non-dairy cattle (Environment and Climate Change Canada 2021c). This margin of error is significant as non-dairy cattle produce 83 per cent of all enteric methane and 71 per cent of agricultural methane overall. Improving upon this estimate requires a comprehensive approach similar to that which was taken for dairy cattle, in which regional animal production characteristics are linked to regional animal productivity (Environment and Climate Change Canada 2021d). This would allow for the replacement of numerous IPCC default parameters with Canada (or North America) specific data.

For manure management, the emission factors are a function of four key variables: the average annual volume of manure produced by animal type, the methane producing potential of the manure, the proportion of manure handled by a specific waste management system (mainly dry or wet) and the methane conversion factor for each system. The NIR uses Canada-specific values for the average annual volume of manure produced by animal type and the proportion of manure handled by each type of waste management system. These values are estimated using data from research studies and farm surveys.[47] They are limited, however, by a lack of data on the regional distribution of manure management systems across Canada and changes in feed composition over time (across all livestock types and animal subcategories).

For the methane-producing potential of manure and the methane conversion factor, the NIR relies on default IPCC Tier 2 parameters. Use of a default value for the methane conversion factor — which represents the percentage of manure's maximum methane-producing capacity under specific management conditions — introduces significant uncertainty to the emissions factors for manure management. Farm-level manure management decisions and systems have a large impact on how much methane is released from manure, especially the frequency and timing of emptying liquid storage tanks. As the IPCC default parameter value does not capture these impacts, the resulting estimates of the manure management emission factors do not adequately reflect variation among farms and regions (Desjardins et al. 2018). For example, the uncertainty range around the mean manure-management emission-factor for dairy cattle is estimated by the NIR at up

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practices generally refers to the intensity of the farming operation. For example whether animals are housed in high-density intensive production systems with animals finished in feedlots or low-density pasturing systems.

[46] Canada relies on default IPCC emission factors instead of country-specific emission factors to estimate enteric methane from non-cattle ruminants.

[47] Three of the key research studies are Marinier, Clark and Wagner-Riddle (Marinier, Clark, and Wagner-Riddle 2004, 2005) and Boadi et al. (2004), with the latter being the same study that is used to calculate emission factors for enteric fermentation.

to 110 per cent, due primarily to use of the IPCC-prescribed default parameters for both the methane conversion factor and the maximum methane producing capacity of manure.[48] VanderZaag et al (2013) suggest the estimates in the NIR model could be improved by developing and applying a matrix of methane conversion factors that accounts for the main factors affecting methane emissions, which would better capture farm management decisions.

More generally, the accuracy of bottom-up estimates depend on the accuracy of emission factors. The accuracy of emission factors in turn depends on the quality and completeness of activity data. Agricultural practices vary widely across Canada, influenced by climate and history, and current estimation models are limited by a lack of compounded, detailed, lower-spatial resolution data representative of this variation (Agriculture and Agri-Food Canada 2008). In particular, current models may not sufficiently account for sub-regional variation in animal production systems, type of feed and feeding practices (Environment and Climate Change Canada 2021c).

A major barrier to collection of more localized emissions data is the cost associated with measurement, reporting and verification of agricultural greenhouse gas emissions and associated reductions — and, in particular, the distributional impacts resulting from the imposition of these costs on agricultural producers (OECD 2019). To reduce farm-level costs associated with measurement, reporting and verification, emission proxies or process-based emissions models can be used instead of more direct forms of measurements. Examples of current practices are to confine a small number of animals in a chamber or instrumented barn or infer emissions through localized atmospheric measurement (Desjardins et al. 2018). These methods of direct measurement are expensive, however, and when extrapolated out to the regional level, may not capture variation in management decisions across farms and changes in practices over time that influence emissions. Instead, indirect methods of estimating enteric methane are increasingly preferred, as they can be less costly, simpler and more accurate than direct measurement of the methane emitted from an animal (Basarab et al. 2013). An example is "residual feed intake," which represents the difference between actual and expected dry matter consumed by an animal. If consumed food is less than expected, then this implies a higher conversion ratio of food to energy or, alternatively, a higher feed efficiency, which in turn implies that less energy is being lost as enteric methane. Indirect measurement methods like residual feed intake are in their infancy and not yet widely implemented, though show great promise for measuring emissions at lower cost.

Waste

All of the methane emissions estimates from Canada's waste sector are calculated using a bottom-up approach. For solid waste landfills, however, the estimation method differs from the usual approach of multiplying an activity measure by an emissions factor. This is because methane emissions from solid waste landfills are a function of cumulative waste volumes. Emissions estimates therefore rely on a sequence of equations that track the inflow of organic waste to landfills, the stock of organic waste from one year to the next, and the amount that decomposes — and generates methane emissions — in any particular year.[49]

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[48] Improvements to the IPCC-prescribed methane conversion factor formula have since been made through the 2019 Refinements to the 2006 IPCC Guidelines (IPCC 2019b).

[49] Specifically, there are five equations that are used in the calculation of methane emissions from each organic material type that enters solid waste landfills. The first equation calculates the annual mass of decomposable organic carbon of that enters provincial landfills each year. The second equation calculates the annual mass of decomposable organic carbon in provincial landfills at the end of each year. This is the stock of organic waste that is subject to decomposition in the next year. It is equal to the flow of waste from the current year, plus the previous year's stock after adjusting for decomposition in the current year. The third equation calculates the mass of organic waste that

The equation sequence used in the NIR follows the IPCC's First Order Decay (FOD) model for estimating methane emissions from solid waste landfills. The IPCC model is a multiphase model that generates methane emissions estimates specific to each type of organic material that enters a landfill. The two key variables in this model, both specific to material type, are the annual flow of degradable organic carbon entering provincial and territorial landfills each year and the rates of decay.

The calculation of the annual flow of degradable organic carbon uses provincial and territorial data on waste volumes and composition, as well as waste-specific DOC and DOC_F values, also generally taken from the IPCC. The final element in this calculation is the methane correction factor (MCF), which varies between 0 and 1 and accounts for any aerobic decomposition of organic waste that may occur within the first year of deposition. As MSW landfills in Canada are managed, anaerobic landfills, the MCF for all waste types is set equal to the IPCC recommended value of 1 (that is, the assumption is that due to daily cover requirements for managed landfills, there is no aerobic decomposition of organic waste). For wood waste landfills, in contrast, the MCF is set at 0.8. This is equal to the IPCC recommended value for unmanaged, deep landfill sites. This value accounts for the fact that wood waste landfills do not have a daily cover requirement and as a result, there will be some decomposition of waste under aerobic conditions.

For MSW landfills, waste volume data goes back to 1941. Notably, there is significant uncertainty in this data. The IPCC characterizes waste data as "high quality" if it is derived from weight measurements at all solid waste disposal sites (IPCC 2019a). Canadian data falls far short of this threshold. Provincial and territorial waste volumes from pre-1980 are calculated using Statistics Canada population data and national per-capita disposal rates, provided in 5- to 20-year increments, from a 1991 consulting report. From 1994 onwards, waste disposal data is calculated from a biennial Statistics Canada waste management survey of industry and government. This data, however, does not include waste volumes that are landfilled. Rather the volume of waste sent to MSW landfills is calculated by subtracting the estimates of waste that are incinerated and exported from total disposal data. Last, for the period of 1981 to 1993, waste volumes are linearly interpolated between the data for 1980 and 1994.

The challenge of low-quality data on waste volumes at MSW landfills is further compounded by a lack of data on waste composition. Provincial waste composition data has only been sporadically collected in three relatively recent studies completed in 2020, 2016 and 2006. These studies are used to estimate composition for the periods of 2015 onwards, 2002 to 2014 and 1976 to 2001 respectively.[50] The waste characterization for prior to 1976 is based on results from a 1973 study of the United States.

For wood waste landfills, waste volume data goes back to 1970. Uncertainty around the volume of waste in wood waste landfills is also high as these landfills are privately operated and publicly available data on volumes sent to them is limited. For most years (1990 to 2010 for the solid wood industry and 1990 to 2004 for the pulp and paper sector), annual estimates of waste depositions are based on three studies from Natural Resources Canada. For the pulp and paper sector, estimates from 2005 onwards are based on a literature review, consultations with industry experts and survey data. For the solid wood waste sector, it is assumed that waste depositions have been zero since 2010. This is attributed to an increasing preference for repurposing wood waste, which in turn has significantly lowered residues. Last, for both

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decomposes in the current year. This is a function of the stock of waste in the landfill at the end of the previous year (equation two) and the rate of decomposition. The fourth equation converts the mass of decomposed organic waste to mass of generated methane. Last, the fifth equation converts generated methane to released methane. Specifically, it adjusts the methane calculated in equation four by accounting for LFG recovery, oxidization by the landfill cover and incomplete combustion of methane at landfill flares.

[50] With municipal recycling programs only commencing in the 1990s, waste that was identified as recycled in the 2006 study was reclassified as landfilled for the period of 1976 to 1989.

the solid wood and pulp and paper industries, annual waste volumes for the period of 1970 to 1989 are assumed to be the same as in 1990 (Environment and Climate Change Canada 2021d).

For MSW landfills, provincial and territorial rates of decay are calculated based on the type of material that is landfilled and the proportion of waste that is landfilled in each climate zone (wet or dry) in each province. The material-specific decay rates for both dry and wet climates are primarily taken from the IPCC guidelines, while the classification of climate zones is based on long-term (1941 to 2018) mean annual climate conditions at the largest landfills in each province. For all provinces' wood-waste landfills, a single rate of decay is used, recommended by the National Council for Air and Stream Improvement Inc.

To obtain the final estimate of landfill methane emissions at the provincial and territorial level, annual decomposition is converted to methane generation and then adjusted for landfill gas recovery and oxidization. The calculations for both MSW and wood waste landfills follow IPCC guidelines in assuming that 50 per cent of the gas generated by landfills is methane and that the oxidization rate is 10 per cent. For MSW landfills, the amount of landfill gas recovery is estimated based on voluntary, biennial survey data. For wood waste landfills, landfill gas recovery is assumed to be zero.

Methane emissions from the biological treatment of solid waste are attributable to both composting and anaerobic digesters. At a composting site, the primarily aerobic conditions mean that waste will typically break down within one-year of being deposited. From a methane emissions perspective, this allows for a much simpler estimation approach as it eliminates the need to track annual decomposition and cumulative waste volumes. Rather, the NIR uses a traditional bottom-up estimation method that multiples an emissions factor (the average amount of methane emissions per kilogram of composted waste) by an activity factor (an annual estimate of diverted organic waste). Both the emissions factor and the activity factor are specific to subtypes of organic waste (yard waste, municipal solid waste, biosolids/manure and a mixture of wastes). The emissions factors for composting were determined from a literature review while the activity factors are facility-specific and derived from industry surveys, technical reports and facility websites (Environment and Climate Change Canada 2021d). Methane emissions from household composting are not accounted for as activity data is not available at the household level.[51]

A modified bottom-up approach is also used to estimate methane emissions from anaerobic digesters. As the intent of anaerobic digesters is to generate methane emissions to use as biogas, the activity factor is biogas production while the emissions factor is the on-site leakage rate. The activity factor is facility-specific and primarily derived from facility-reported survey data. The emissions factor is constant across all facilities and based on both primary literature and survey data (Environment and Climate Change Canada 2021d). Not included in the methane emissions estimate for anaerobic digesters are emissions attributable to venting, biogas upgrading and incomplete combustion.

The NIR estimate of methane emissions from the wastewater sector is divided into three separate sources: wastewater treatment, the anaerobic digestion of sludge and discharge to receiving water bodies. Methane emissions from each source are calculated by treatment technology at the provincial level and then summed to obtain a national total. Emissions from both wastewater treatment and from discharge to receiving water bodies are calculated using a bottom-up approach, while emissions from anaerobic digestion are calculated based on an assumed rate of incomplete combustion of methane and leakage.

The starting point for estimating methane emissions from the wastewater sector is the calculation of total annual organic load that enters the wastewater system. At the provincial level, this is a function of the per

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[51] In 2011, 32 per cent of all households that composted yard waste and 41 per cent of all households that composted kitchen waste deposited at least a portion of these wastes in a household bin or pile (Mustapha 2013). More recent data on household-level composting is not available. It is reasonable to expect, however, that these percentages have gone down since 2011 as more municipalities have introduced curbside composting programs over this period.

capita organic loading rate (BOD_5/capita/day), a correction factor to account for industrial and commercial inputs to municipal wastewater, and the population in each province. Both the per capita organic loading rate and the correction factor equal the IPCC default values. The total provincial organic load is then allocated across treatment technologies based on the estimates of the population share that is served by each type of technology. For example, if 25 per cent of a province's population is estimated to use a septic system then the organic load attributed to septic systems is equal to 25 per cent of the province's total organic load.

For each type of wastewater treatment technology, the activity factor for methane emissions from wastewater treatment is equal to the organic load allocated to that technology minus an estimate of the organic load that is removed from the system as sludge. The activity factor for methane emissions from wastewater discharge is similarly treatment technology specific and is equal to an estimate of the remaining organic load in wastewater after treatment. The NIR estimates of the sludge removal factors and the BOD_5 removal efficiencies of the wastewater treatment systems draw on a range of sources including the IPCC guidelines, internal analysis by ECCC and literature reviews.

For both wastewater treatment and wastewater discharge, the emissions factor is equal to the maximum methane producing capacity per unit of BOD_5 in wastewater, multiplied by an MCF. For the theoretical maximum methane producing capacity of wastewater, the NIR uses a single, Canada-specific value that was derived in a 2011 consulting report. The Canada-specific value is 40 per cent lower than the IPCC default and likely captures the negative impact of colder temperatures on methanogenic activity. The MCF is technology-specific for wastewater treatment as it captures the degree to which the treatment technology is anaerobic.[52] For wastewater discharge, the MCF is constant across all technologies as all discharge tends to enter an open water body. The MCFs for both wastewater treatment and wastewater discharge are generally equal to IPCC default parameter values.

Last, the calculation of released methane emissions from the anaerobic digestion of sludge depends on an estimate of total generated methane emissions from the anaerobic digestion process, multiplied by a rate that accounts for fugitive loss and combustion inefficiency. This rate is constant across all treatment technologies. The estimate of total generated methane emissions is technology-specific and starts with the estimate of the organic load contained in sludge removal. This estimate then passes through a series of technology-specific equations that determines the mass of total suspended solids in the sludge reduced by anaerobic digestion. These equations also determine the quantities of sludge that may be redirected to other types of waste treatment such as landfills. The parameters for these equations are largely derived from a 2019 consulting report.

Despite the use of site-specific, province-specific and Canada-specific data and parameter values there is still large uncertainty associated with the estimate of methane emissions from wastewater. This is consistent with the other waste subsectors, with the overall IPCC waste category being one of the most dynamic and challenging categories for which to obtain emissions estimates.

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[52] For example, the methane correction factor for an aerobic lagoon is zero, as the aerobic conditions of the lagoon mean that zero methane emissions will be released from decomposition. In contrast, the methane correction factor for an anaerobic lagoon is 0.8, meaning that 80 per cent of the maximum methane emissions will be released during the decomposition process (Environment and Climate Change Canada 2021d).

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